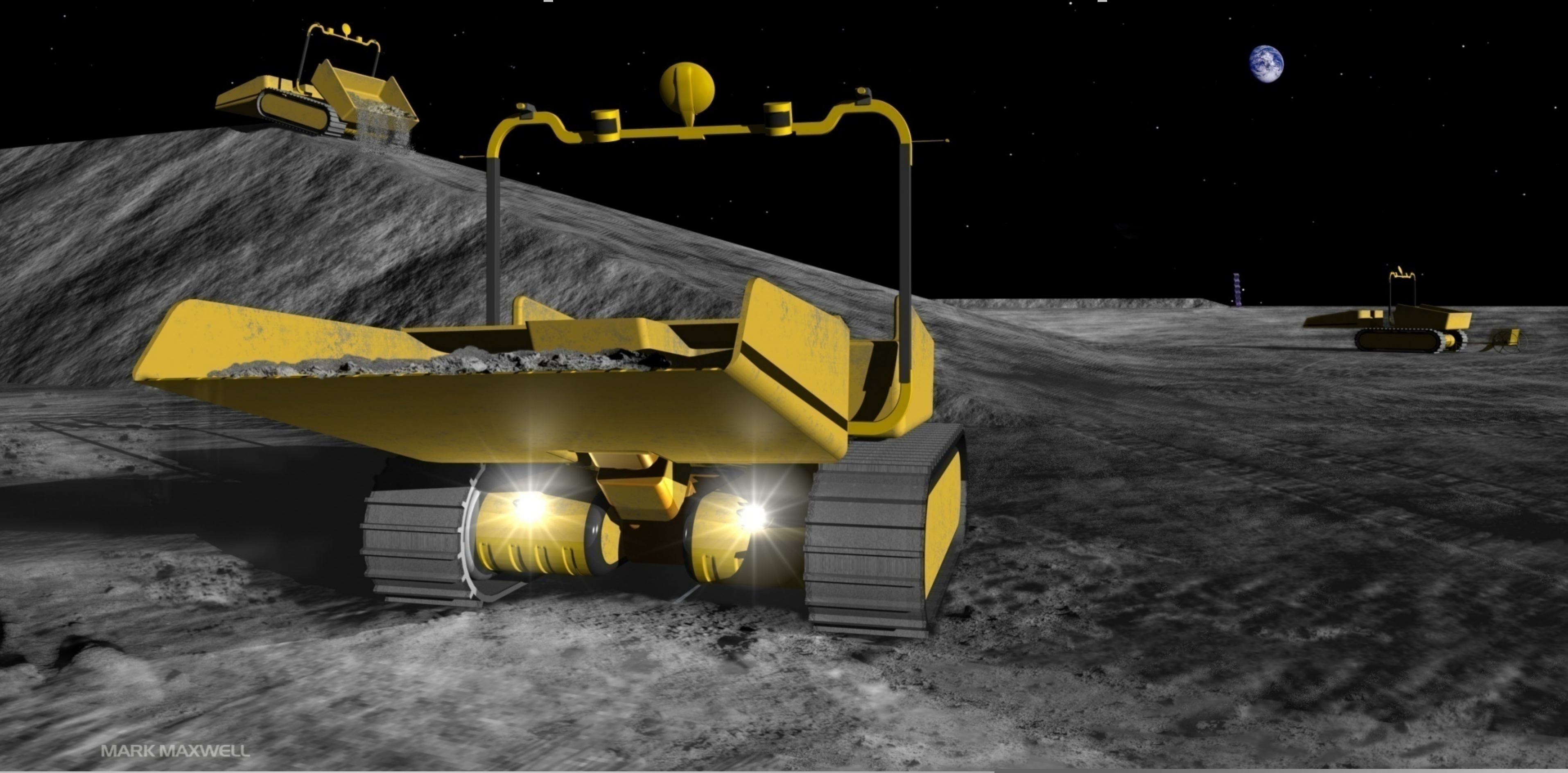
Configuring Innovative Regolith Moving Techniques for Lunar Outposts



U.S. Chamber of Commerce Programmatic Workshop on NASA Lunar Surface Systems Concepts

Feb. 27, 2009

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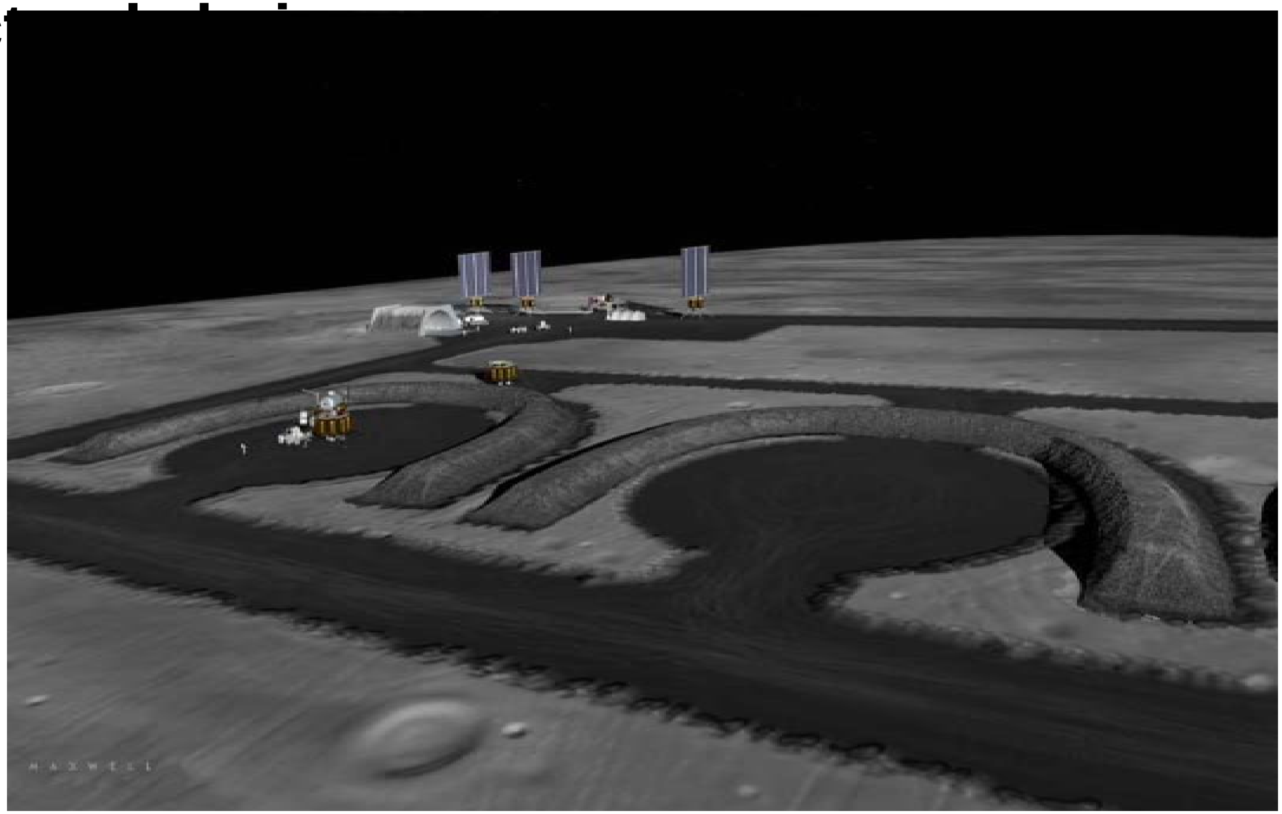
Lunar Outpost Preparation

- **Regolith moving for site preparation would occur early in lunar outpost operations, and effectiveness impacts architect**



[Image Courtesy of Mueller and King, STAIF 08]

- **Regolith moving opportunities include site and road leveling, obstacle clearing, habitat and cable trenching, berm construction, surface stabilization, and radiation shielding**

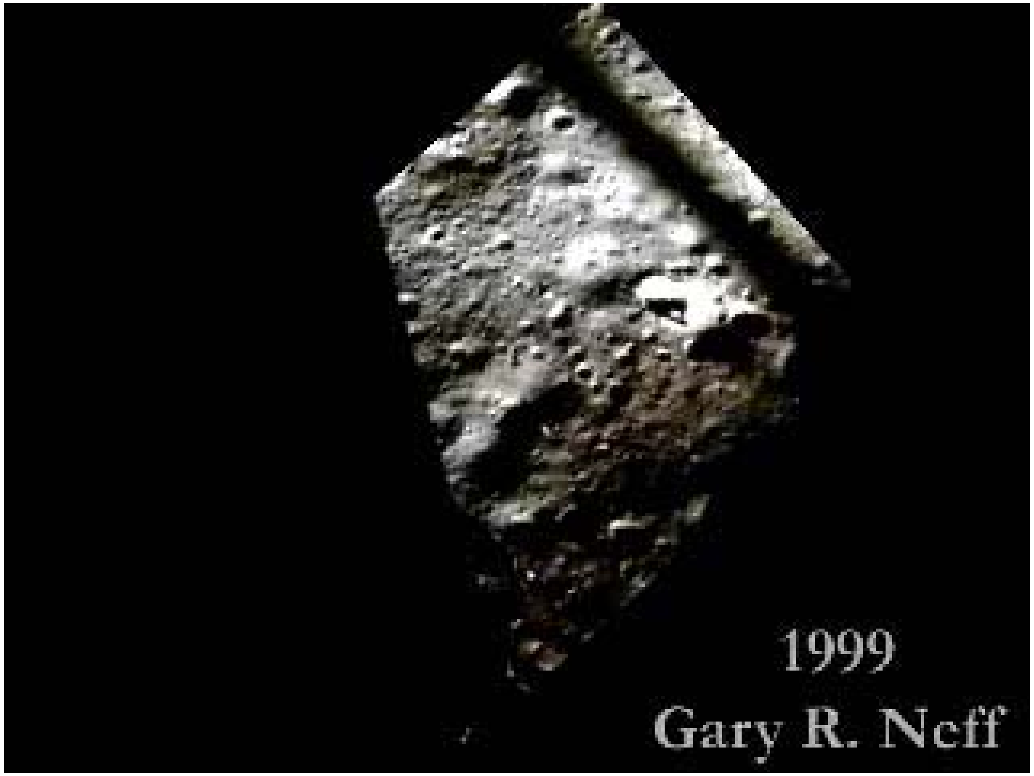
Questions about Robotic Lunar Construction

Questions concerning robotic lunar construction answered by this program:

- **How much could be constructed with excavation robots of mass less than 300 kg?**
- **What are key parameters that affect construction feasibility and completion time?**
- **Are there innovative ways to accomplish site preparation and surface stabilization using native lunar materials?**
- **What lunar data is still required to ensure robotic construction success?**

Example Task: Berm Construction

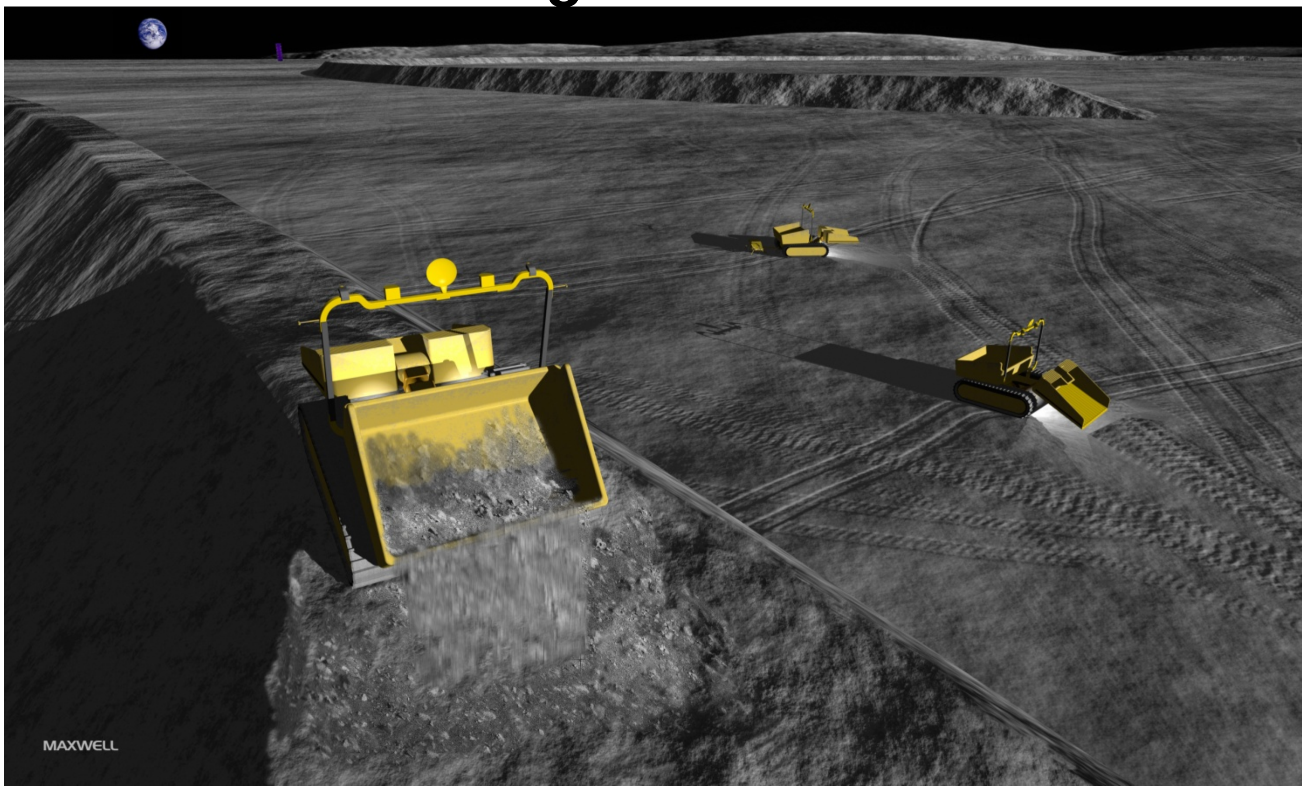
- Blast erosion from multiple landings / takeoffs must be contained or suppressed by:
  - Berm construction
  - Surface stabilization



- Berm construction is a useful task to study because it comprises the elemental actions of digging, transporting, dumping, compacting, and shuttling for recharge

Berm Construction with Small Excavation Robots

- **How much could be constructed with excavation robots of mass less than 300 kg?**



Robots with mass of 300 kg or less are capable of constructing a protective berm at a lunar polar outpost in less than 6 months, if equipped with dump beds (bins for accumulating regolith from multiple excavation bucket loads)

Key Berm Construction Parameters

- **What are key parameters that affect berm construction feasibility and completion time?**

Driving speed and Payload ratio (ratio of regolith mass carried to empty system mass) are the two parameters that most affect task completion time for vehicles with dump beds

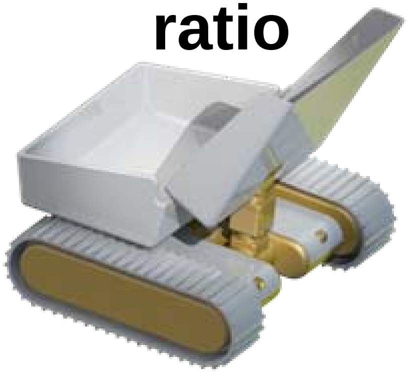
Regolith cohesion is the most significant parameter that is outside the designer's control

- **Cohesion refers to the component of regolith strength that is caused by mechanical interlocking of particles and is independent of interparticle friction**

Innovative Regolith Moving Techniques

- Are there innovative ways to accomplish site preparation and surface stabilization utilizing native lunar materials?

Include a dump bed to achieve sufficient payload ratio



Perform rock paving to stabilize surface using native lunar materials

Use vibration and downforce to compact regolith for strength

Outpost Scouting Mission

- **What lunar data is still required to ensure robotic construction success?**

Excavation resistance force of regolith has not been characterized in the lunar environment

- Excavation resistance is a function of the full tool/soil interface (measured with a test bucket) and is more comprehensive than soil properties such as cohesion (derived from cone penetrometers, etc.)

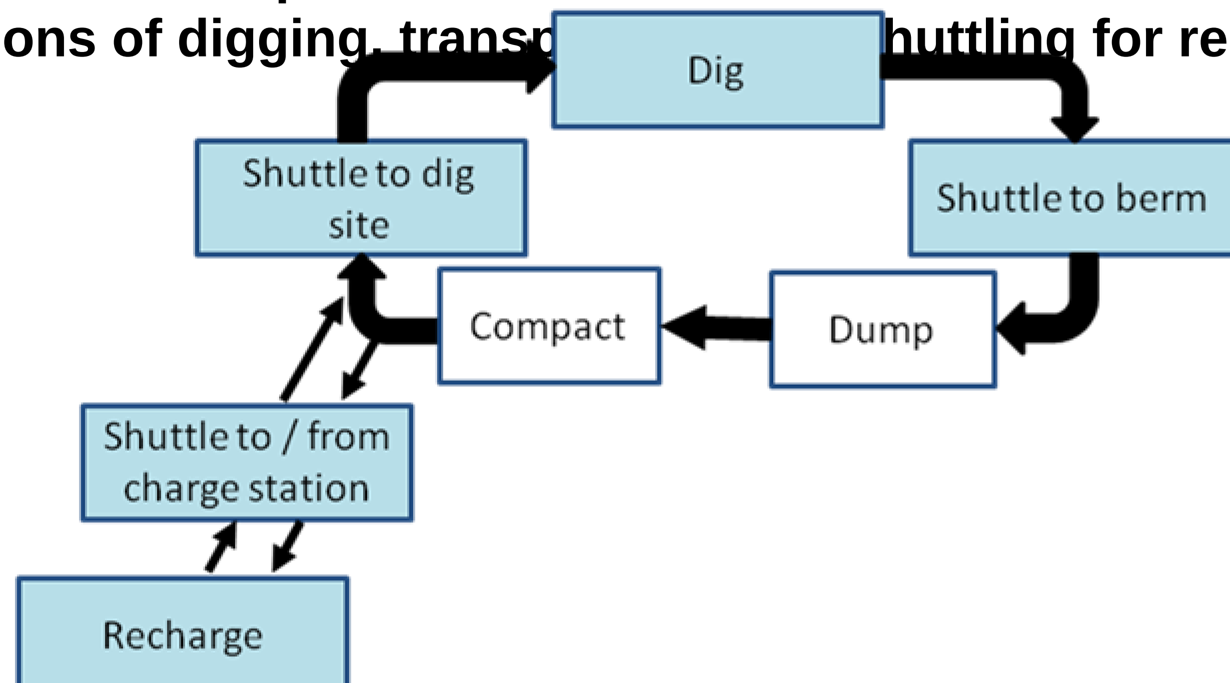
Distribution and abundance of rocks at the lunar poles is unknown

- Rock paving can only work if there are enough rocks within a feasible collection area

REMOTE: Regolith Excavation, MObility & Tooling Environment

- **Conclusions derived from analysis of task simulations, modeled in REMOTE**

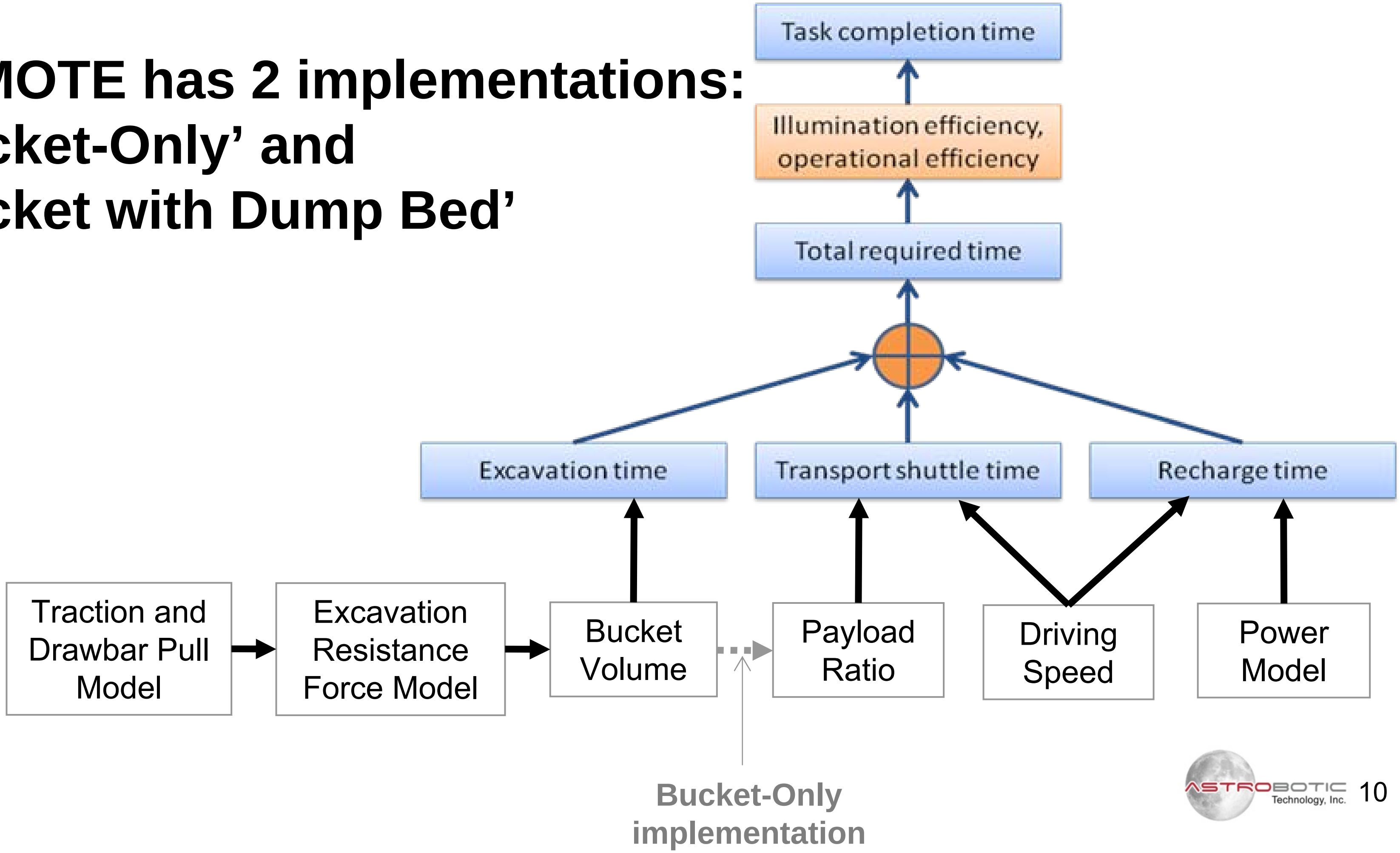
- **REMOTE characterizes performance of machines within site-level tasks such as berm building, trenching, and road building**
  - **Creates a comprehensive context for a task from the elemental actions of digging, transp huttling for recharge**



Task Simulation: REMOTE

- **Task completion time is calculated from durations of elemental actions, which are underpinned by analytic models of traction, excavation resistance force, etc.**

- **REMOTE has 2 implementations: 'Bucket-Only' and 'Bucket with Dump Bed'**



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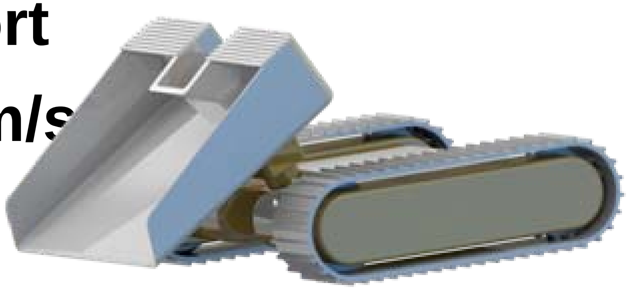
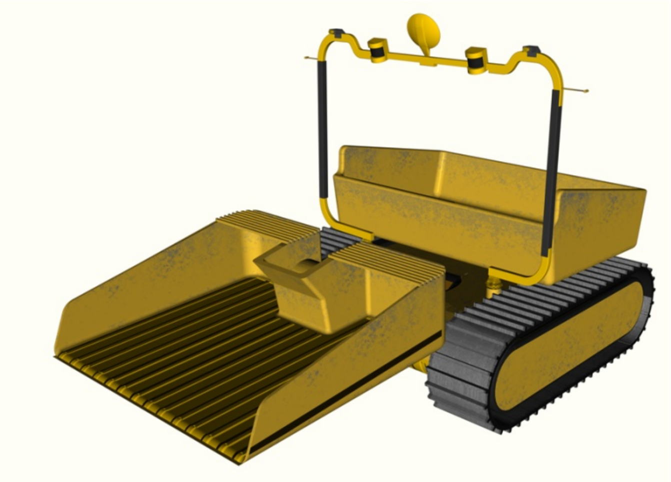
Berm Construction Simulation: Bucket-Only

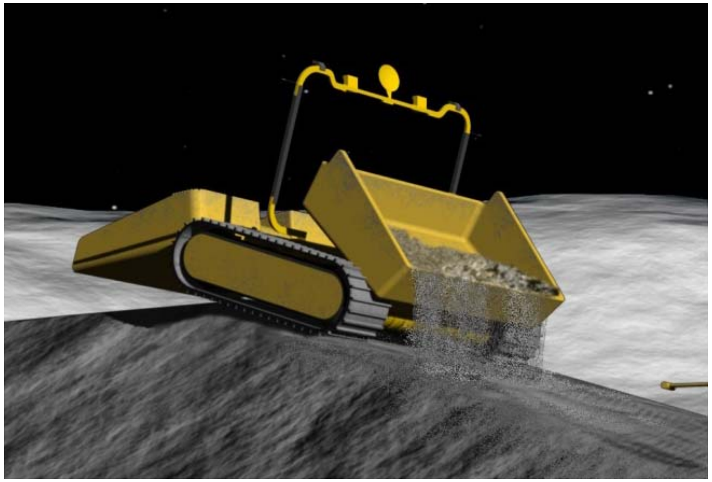
- **Small excavation robots with buckets as their only regolith carrying containers can complete a berm in 1170 days (over 3 years)**

- **Some of the simulated parameters and values that lead to this result:**
  - ➢ **2 excavation robots, each of mass 150 kg**
  - ➢ **1,200,000 kg of regolith to transport**
  - ➢ **Transport shuttle velocity of 15 cm/s**
  - ➢ **4% Payload ratio output by simulation**



Berm Construction Simulation: Dump Bed

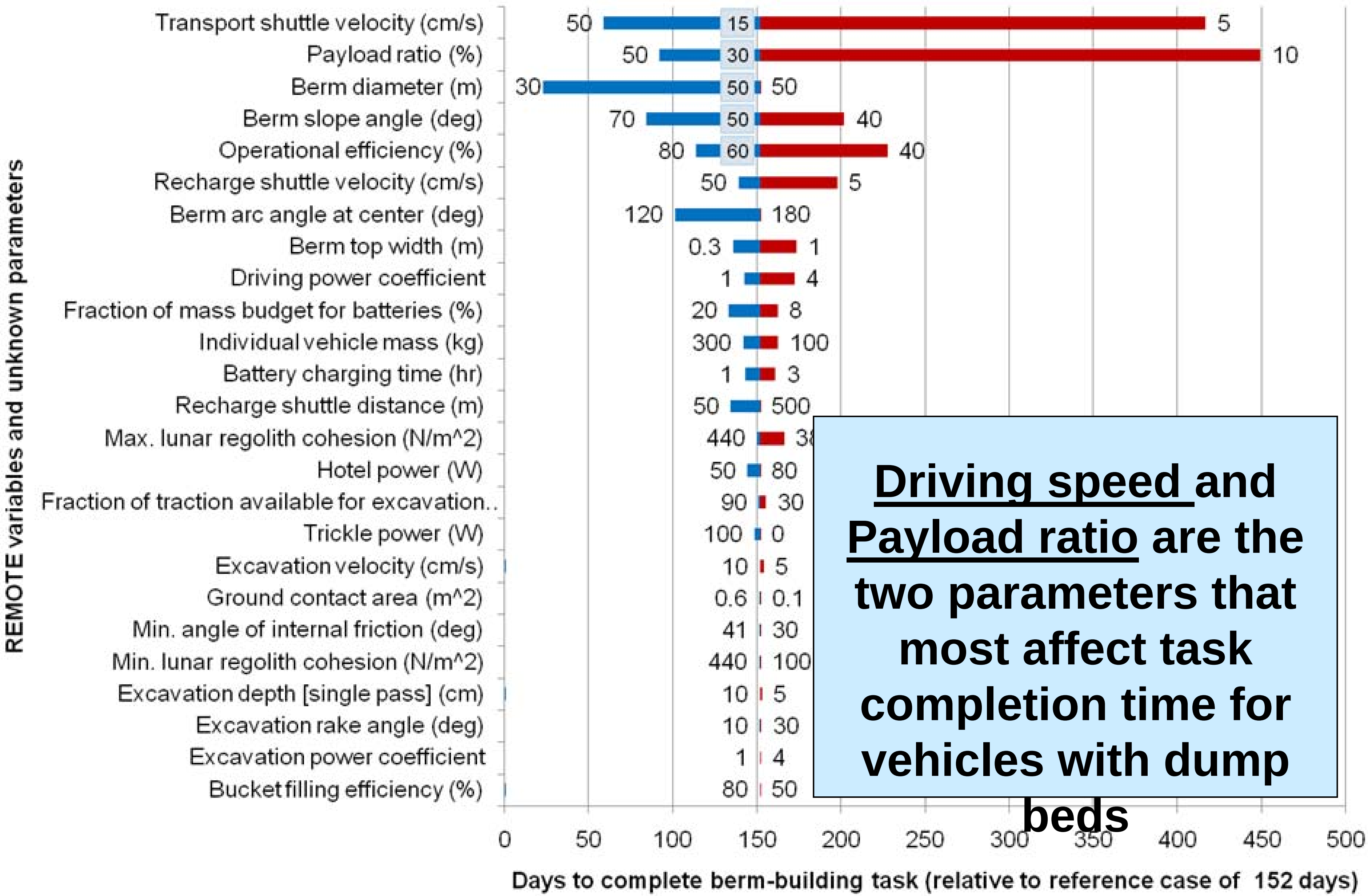




- **Small excavation robots with dump beds for accumulating regolith can complete a berm in 152 days (5 months)**
- **Parameters and values that lead to this result are the same as for the Bucket-only case, except for Payload ratio:**
  - **2 excavation robots, each of mass 150 kg**
  - **1,200,000 kg of regolith to transport**
  - **Transport shuttle velocity of 15 cm/s**

Robots with mass of 300 kg or less could construct a protective berm (50 m diameter semi-circle, 2.6 m height) at a lunar polar outpost in less than 6 months, if equipped with dump beds

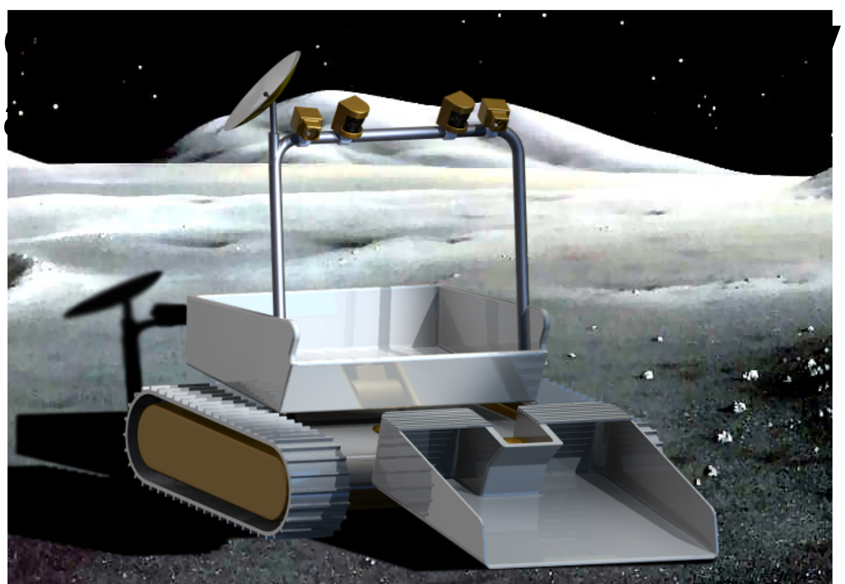
Sensitivity Analysis of Dump Bed Implementation



<u>Driving speed</u> and <u>Payload ratio</u> are the two parameters that most affect task completion time for vehicles with dump beds

Transport Shuttle Velocity

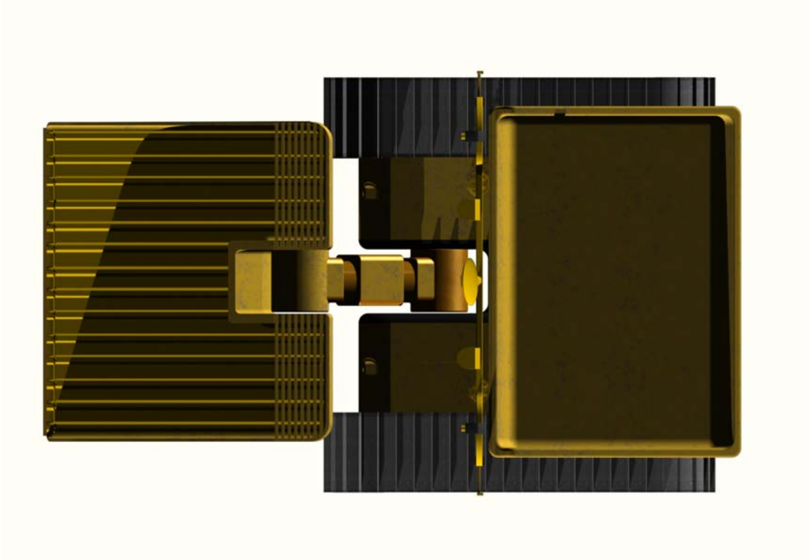
- **Berm construction with small excavation robots is mostly driving**
  - **Approximately ¾ of total required time is transport shuttle time**
- **Without onboard astronaut drivers, lunar vehicle speeds will be limited by the capabilities** … **ised**



An extraterrestrial vehicle cannot be expected to drive this fast…

Payload Ratio

- Payload ratio directly affects the number of transport shuttle trips required between dig and dump
- As berm construction is mostly driving, completion time is sensitive to driving speed and number of driving trips
- Without a dump bed, payload ratio depends on excavation parameters that may vary significantly and some of which are outside the designer's control



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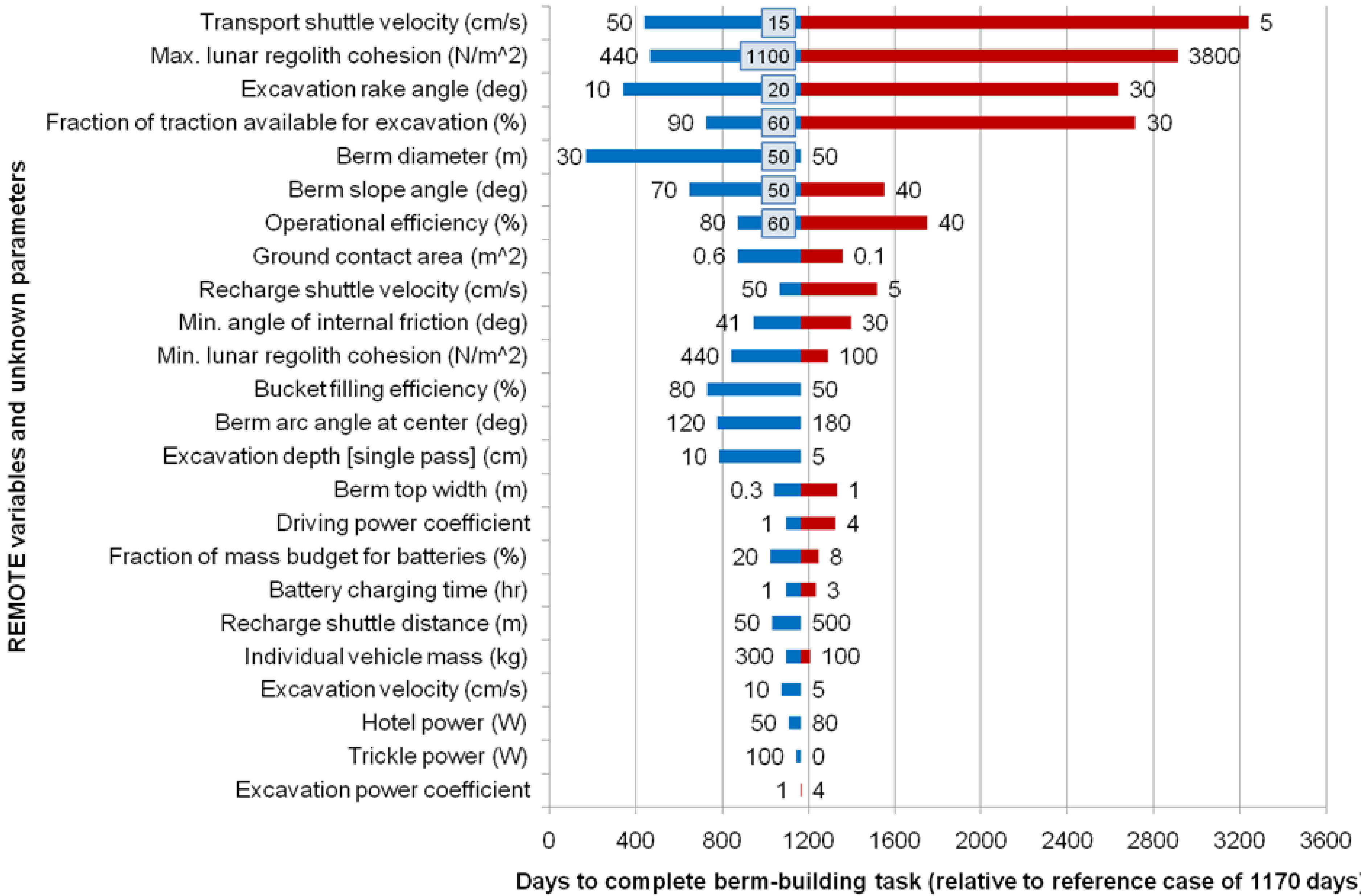
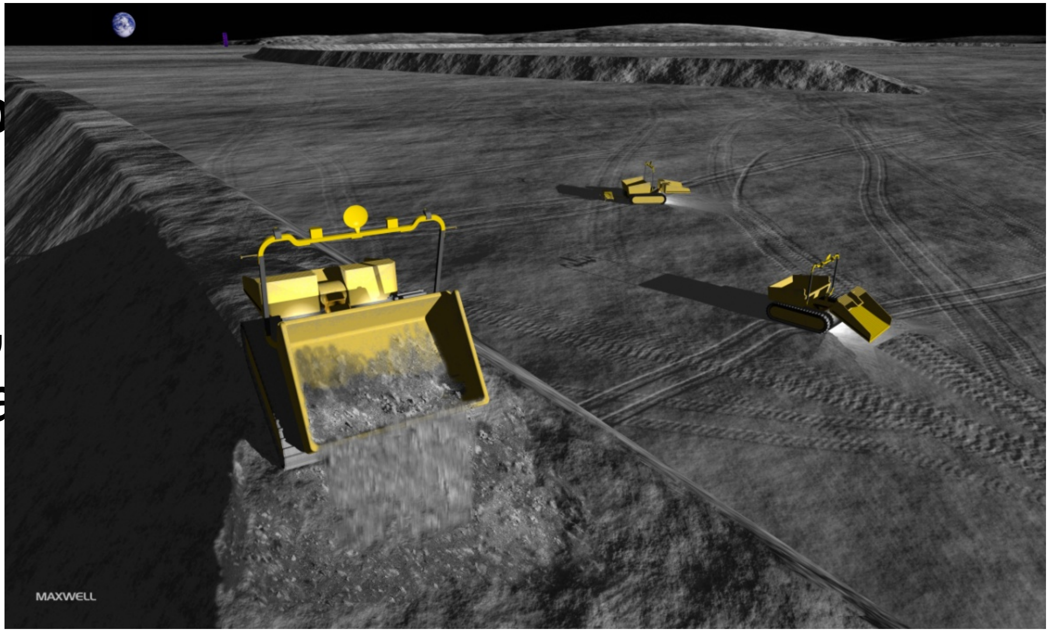
Sensitivity Analysis of Bucket-only Implementation



Innovative Regolith Moving: Dump Bed

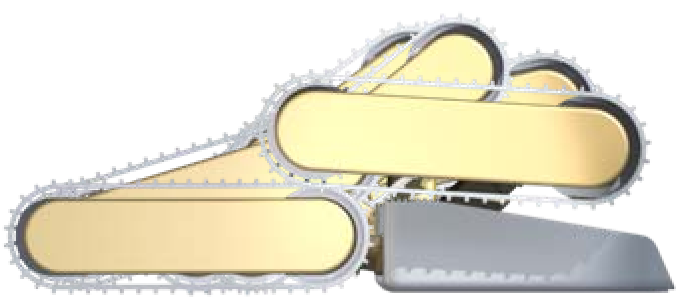
- A dump bed…
  - Reduces the number of transport shuttle trips required, making 6 month berm construction feasible
  - Makes payload ratio a design parameter, instead of being dependent on the excavation reaction forces
  - Reduces the effect of regolith cohesion o completion time

- Dump beds do, however, require additional mass a complexity compared to a bucket-only design



Innovative Construction: Compaction

- **Compacting (packing) regolith increases density and interparticle contact, improving strength and bearing capacity**
  - A compacted berm can be driven on by small excavation robots
- **Compaction can reduce the quantity of regolith require**
- **Vibration and downforce are effective means to compact**
- **Loader/Compactor Concept: Combine a flat bottomed excavation bucket with r tory actuator**

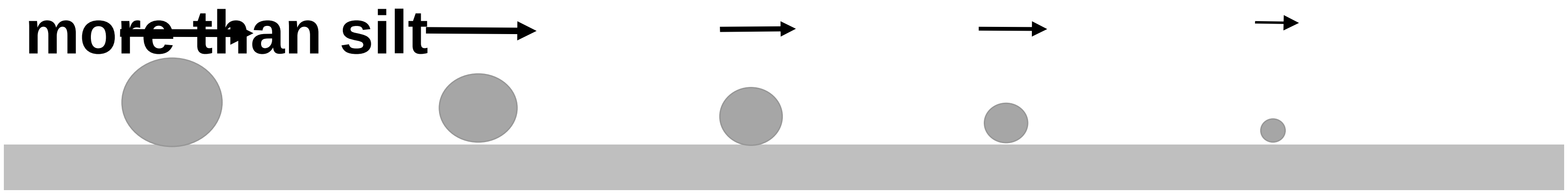


Innovative Surface Stabilization: Rock-Paving

- Rock-paving could suppress surface d during takeoff / landing without sinteri chemical binding, or geotextiles

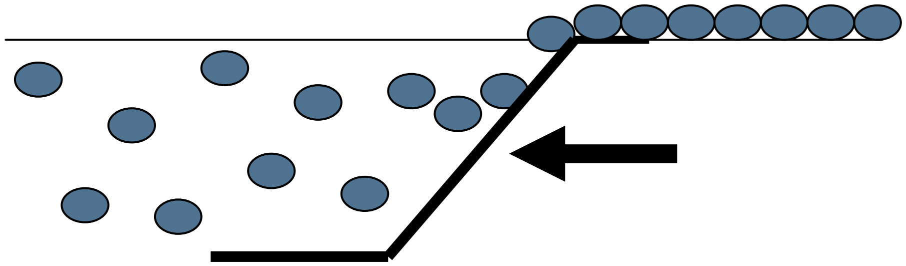
- This technique is used for constructing stream-crossings, spillway linin and road-edges on Earth, and r have utility on the Moon

- Rocks resist erosion more than gravel; gravel resists erosion more than sand; and sand resists erosion more than silt

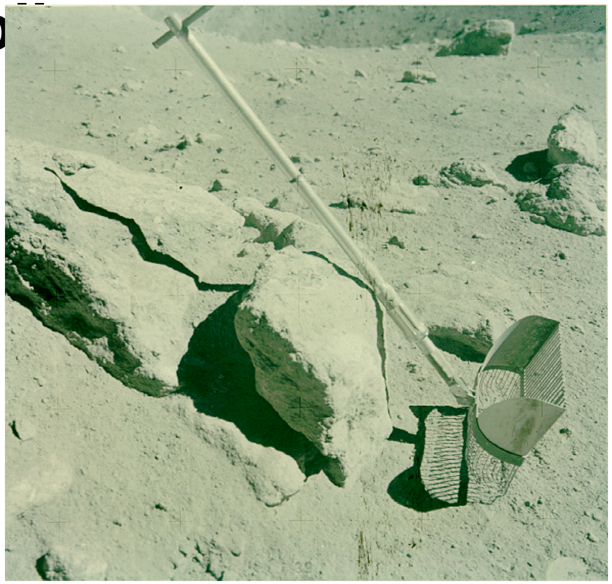


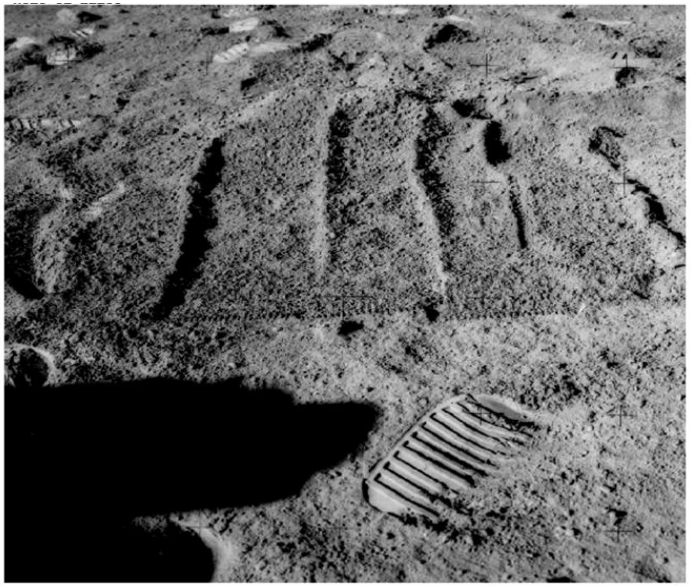
Rock-Paving Rake

- **A rock-paving rake raises buried rocks to the surface:**



- **Rock rakes were used for sample collection during Apo**





Rock Rakes, Windrowers and Rock-Pickers

- **Rock rakes, windrowers, and rock-pickers are used to collect, separate, or move rocks in agricultural applications**

- **The rock rake concept, along with windrowers and rock-pickers, could be developed into machines for lunar surface stabilization**

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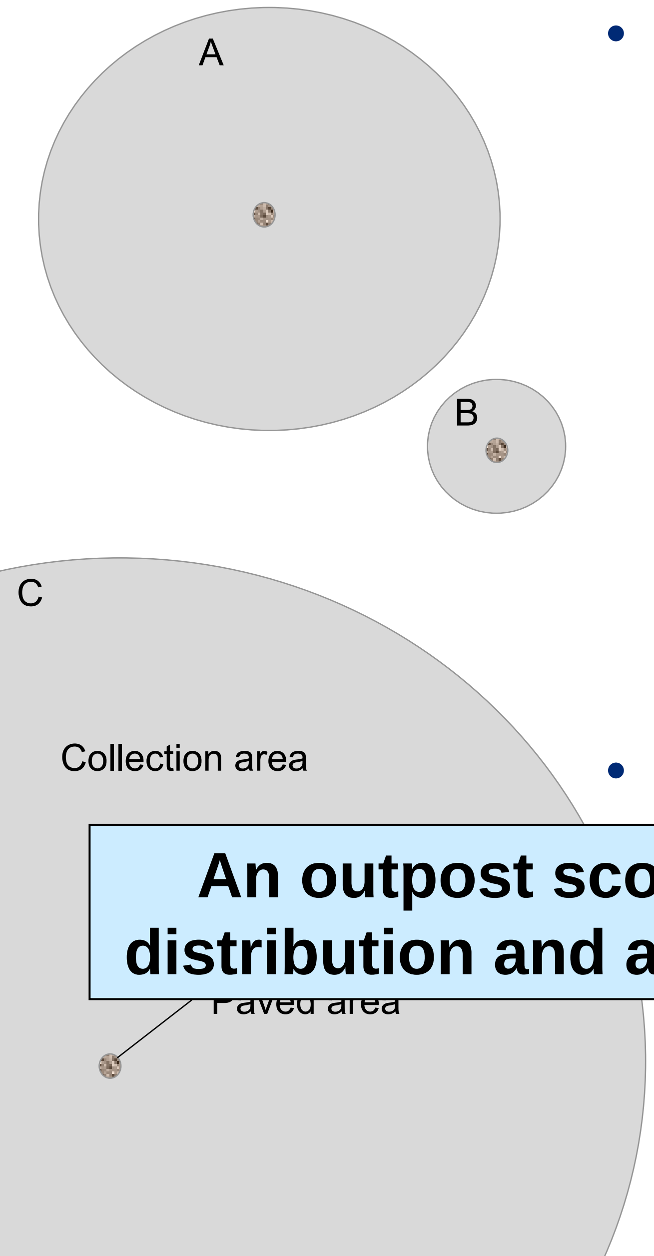
Use of Native Lunar Rocks



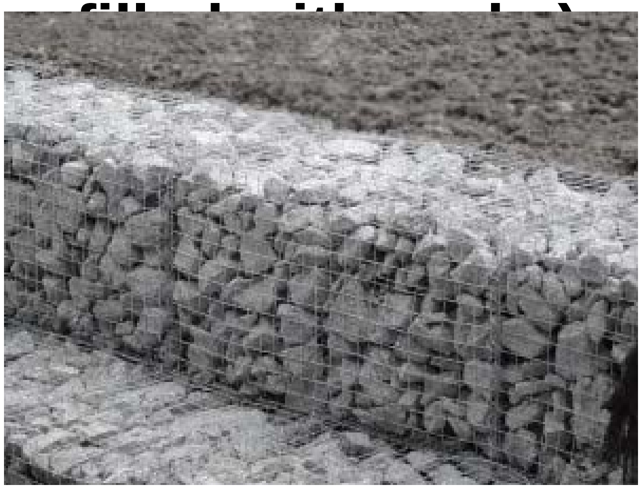
- **Feasibility of rock paving depends on:**
  - Size of rock required to resist blast erosion: 10-15 cm diameter particles are thought to be sufficient
  - Abundance and distribution of rocks at lunar poles
  - Rake depth (depth from which rocks are collected)
- **Sample cases based on rock**

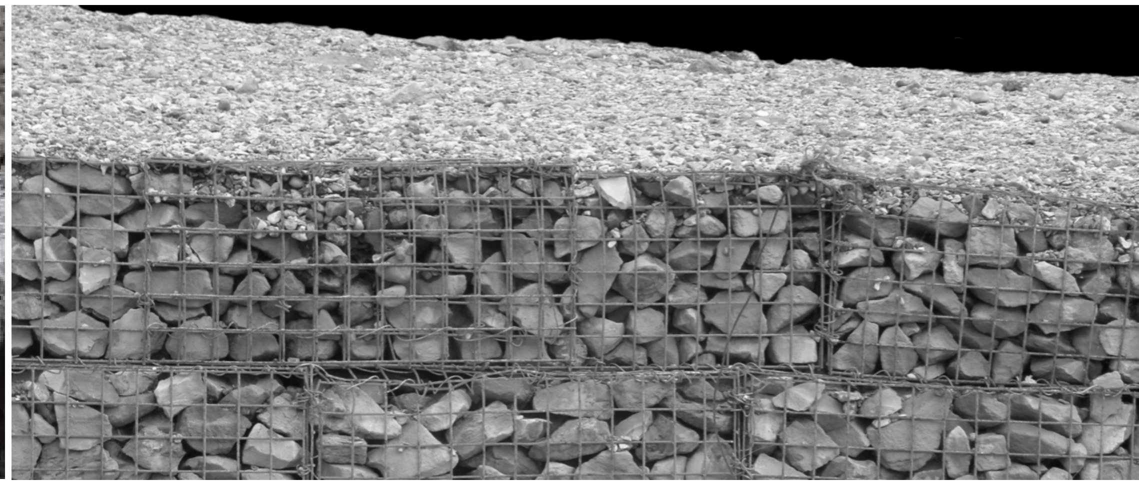
An outpost scouting mission could determine the distribution and al

Case	Rock size	Rake Depth	Drive Distance
A	1 – 2 cm	Surface	1400 km
B	1 – 2 cm	15 cm	180 km
C	10 – 15 cm	Surface	11,000 km

Gabion Boxes

- **If adequately sized rocks are not abundant at potential lunar outpost sites, smaller rocks could still provide stabilization if contained within gabion boxes (cages filled with rocks)**





- **Combining the concepts of rock paving with gabion-like geotextiles could decrease the mass of geotextile required to stabilize a surface**
  - ➢ Containing larger rocks (collected and paved) requires a sparser mesh than containing average regolith particles

Excavation Resistance Force

- **Excavation resistance is the force required to pass a tool (bucket) through regolith**

- **Excavation resistance encompasses cohesion (which is one of the most significant parameters in all excavation resistance force models, and is significant in task completion time)**
  - Excavation resistance can be measured with a test bucket analogous to one designed for an eventual excavation robot

An outpost scouting mission could characterize excavation resistance force for lunar regolith

Current Knowledge of Lunar Excavation Resistance

- **Excavation resistance is correlated with cohesion, which is known for lunar regolith, but only for equatorial, intercrater areas (even then, great variability is observed with locale and depth)**
  - Example: At 30 cm depth, cohesion value could be anywhere between 0.74 kPa and 3.8 kPa

TABLE 9.12. Recommended typical values of lunar soil cohesion and friction angle (intercrater areas).

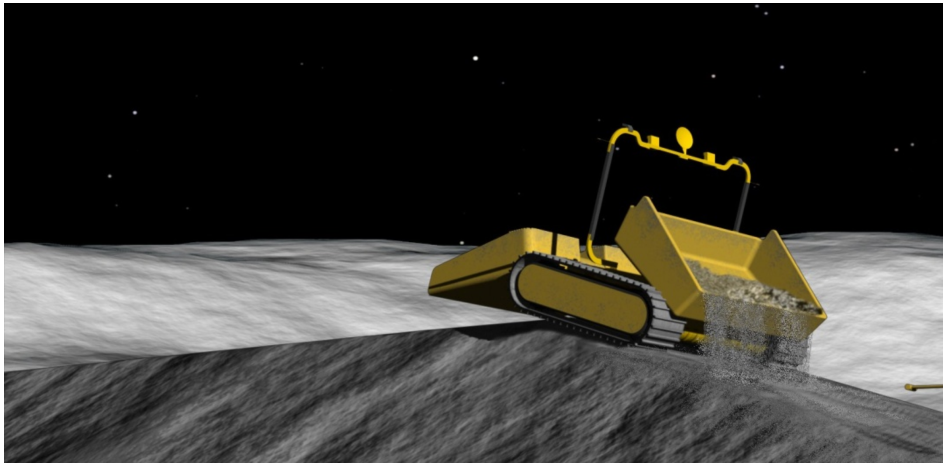
Depth Range (cm)	Cohesion, c (kPa)		Friction Angle, ϕ (degrees)	
	Average	Range	Average	Range
0 – 15	0.52	0.44 – 0.62	42	41 – 43
0 – 30	0.90	0.74 – 1.1	46	44 – 47
30 – 60	3.0	2.4 – 3.8	54	52 – 55
0 – 60	1.6	1.3 – 1.9	49	48 – 51

[Lunar Sourcebook]

Summary

- **Robots with mass of 300 kg or less could construct a berm in less than 6 months, if equipped with dump beds**

➢ REMOTE simulates task-level operations, such as berm construction, by combining analytical models of elemental actions such as excavation and mobility

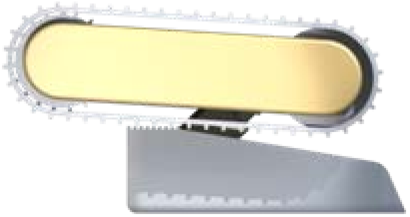


- **Driving speed and payload ratio are the two parameters that most affect task completion time for vehicles with dump beds**

➢ REMOTE identifies key parameters to construction task completion time by means of sensitivity analysis

Summary

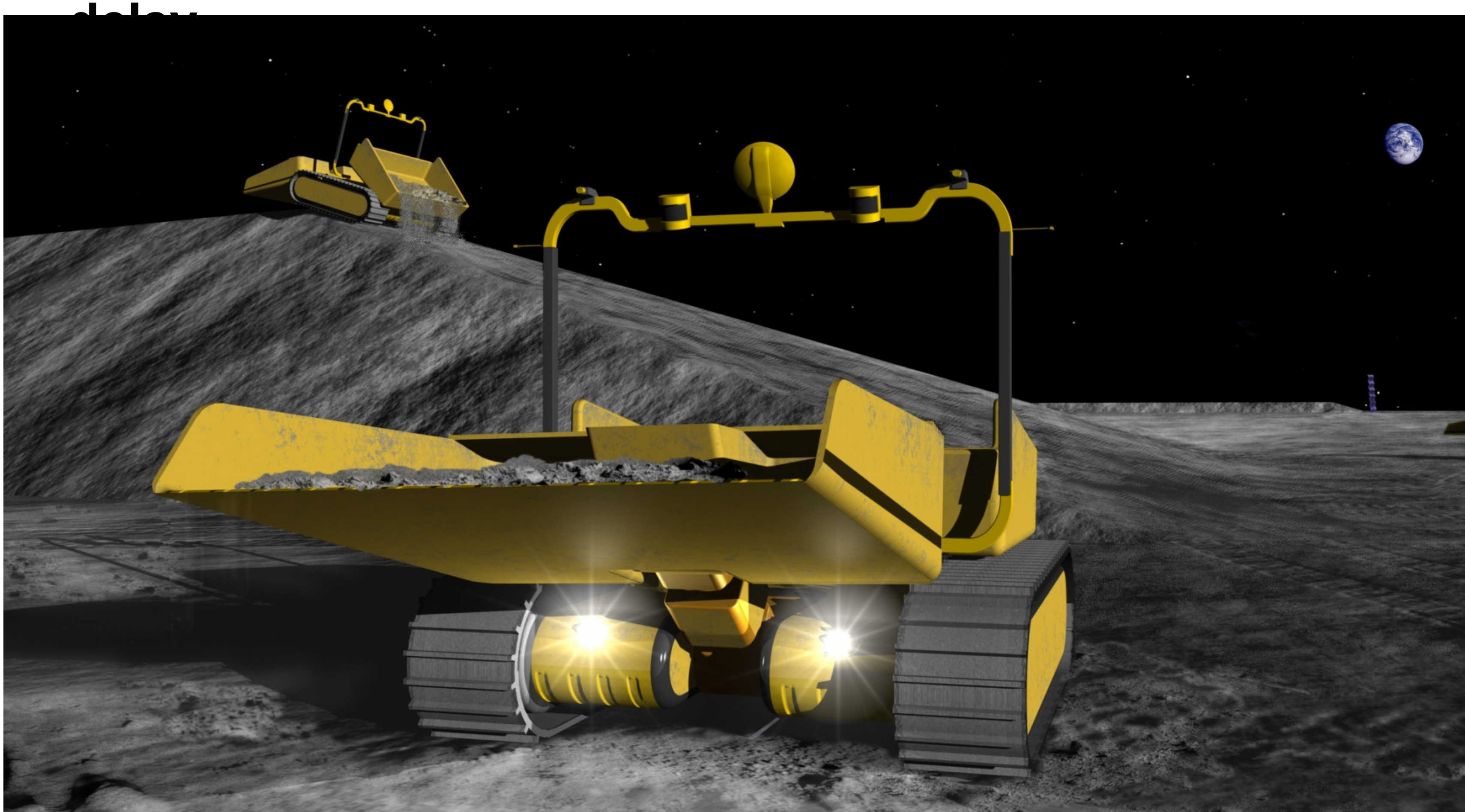
- **Innovative regolith moving techniques include:**
  - **Using vehicles equipped with dump beds**
  - **Compacting with a dual loader/compactor**
  - **Stabilizing a landing pad by rock paving**



- **Effectiveness of construction and rock paving depend on further lunar data:**
  - **Measuring excavation resistance force directly**
  - **Determining distribution of lunar rocks**

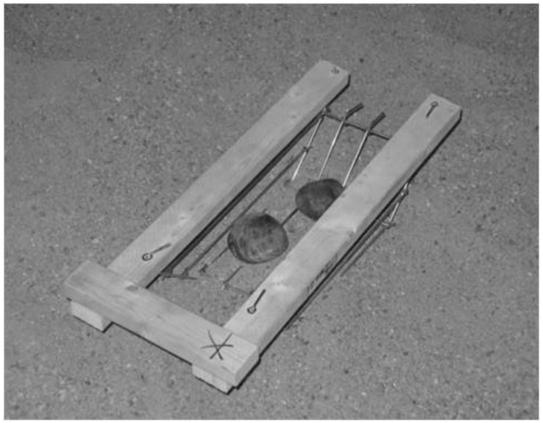
Opportunities for Follow-on Work: Moon Digger

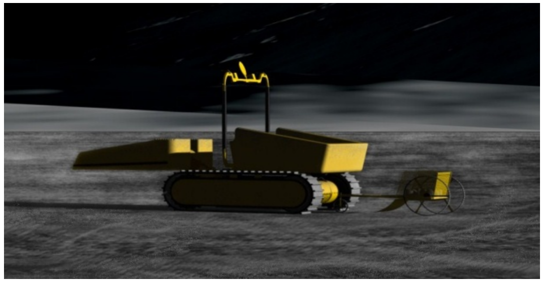
- **Analyze, prototype, and evaluate:**
  - **Technical implementations for bucket and dump bed designs**
  - **Teleoperation and automation of regolith moving with time delay**



Opportunities for Follow-on Work: Rock Paver

- **Construct, prototype, and experiment:**
  - **Technical solution to rock collection and dissemination for paving/surface stabilization (and clearing zones)**
  - **Resistance force evaluation to determine suitable raking depth**





Questions?

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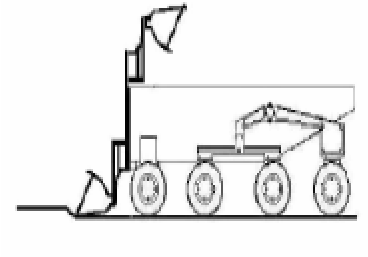
Backups

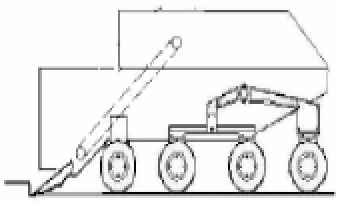
Examples of dump beds

- **Overshot loader:**

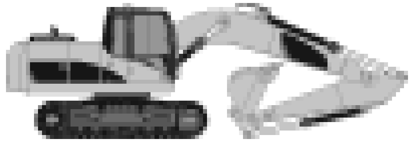


Towed:

- **Scraper:**

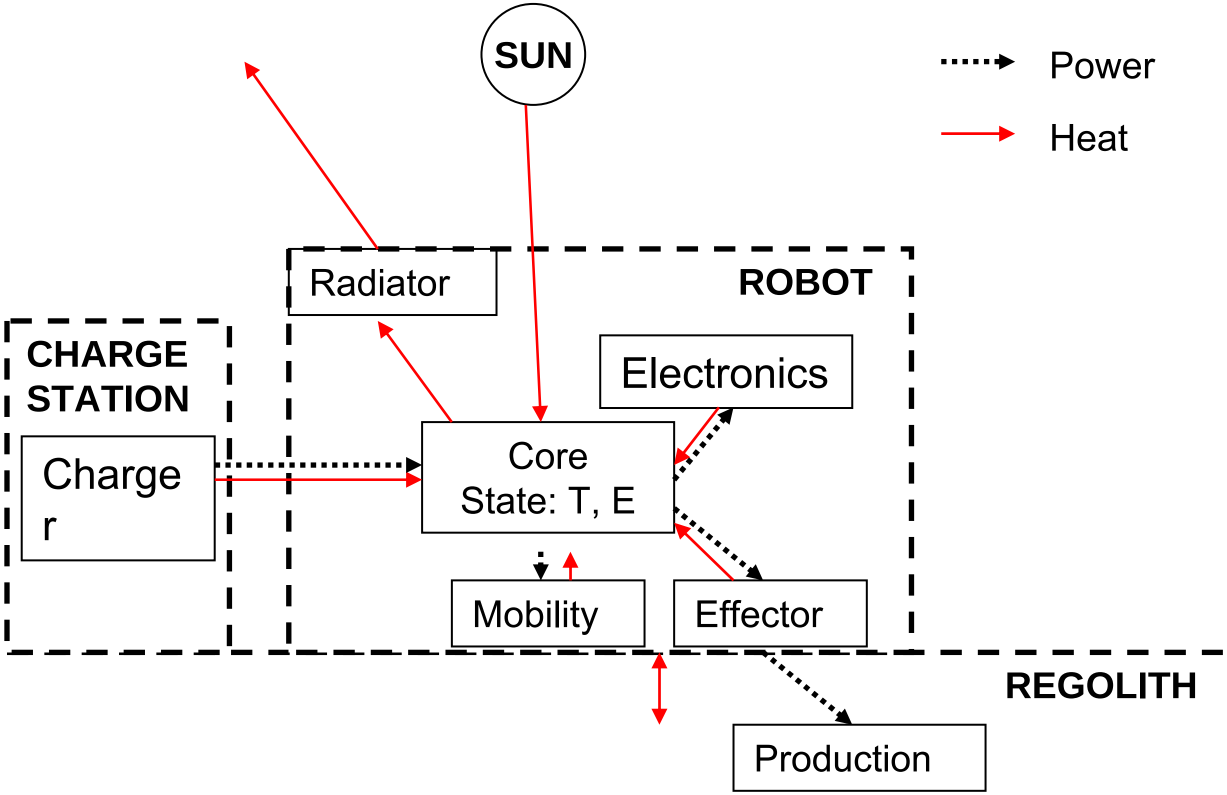


- **Hauler teamed with excavator or loader:**



REMOTE (Regolith Excavation, MObility, & Tooling Environment)

- **Modeling environment that enables task-level performance analysis**
- **Can be implemented for various mobility, tooling and work-function designs**



REMOTE – Mobility subsystem

- **Maximum tractive force for a wheel loader was estimated using Mohr-Coulomb relation for maximum soil shear strength:**

$$T^{\max} = cA_G + mg\tan\varphi$$

where c is cohesion, g is gravitational acceleration (1.62 m/s^2), φ is angle of internal friction, A_G is the ground contact area, and m is the system mass

REMOTE – Mobility subsystem

- **Drawbar pull is the net tractive force available for work after accounting for losses such as slip and rolling resistance**
- **Slip and rolling resistance are not modeled directly; losses are taken into account by an estimated aggregate scaling factor: "Fraction of traction available for excavation"**

$$DP = K_{HfT} T^{max}$$

where DP **is drawbar pull,** T^{max} **is maximum tractive force, and** K_{HfT} **is fraction of traction available for excavation**

REMOTE – End Effector subsystem

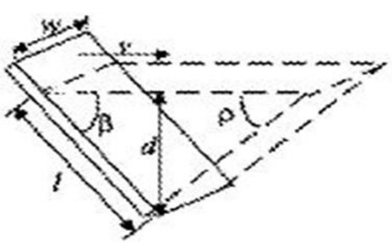
- **Drawbar pull is equated to the excavation force, H_f, which is calculated based on the Viking excavation**

$$H_{\text{friction}} = \gamma g w l^{1.5} \beta^{1.73} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{0.77} \times \left\{ 1.05 \left(\frac{d}{w} \right)^{1.1} + 1.26 \frac{v^2}{gl} + 3.91 \right\}$$

$$H_{\text{cohesion}} = \gamma g w l^{1.5} \beta^{1.15} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{1.21} \times \left\{ \left(\frac{11.5c}{\gamma g d} \right)^{1.21} \left(\frac{2v}{3w} \right)^{0.121} \left(0.055 \left(\frac{d}{w} \right)^{0.78} + 0.065 \right) + 0.64 \frac{v^2}{gl} \right\},$$

[Wilkinson 07]

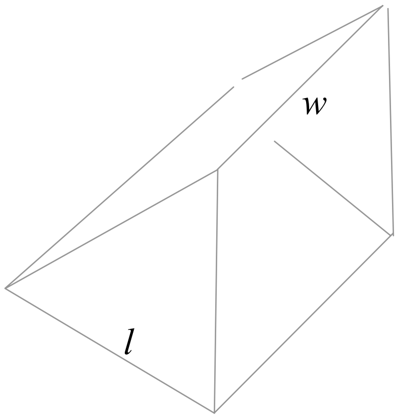
- **Horizontal excavation force is used to solve for loader blade geometry**
  - Digging depth, d , digging angle, β, and blade length, l, all specified
  - Blade width, w, left as dependent variable



REMOTE – End Effector subsystem

- **Bucket volume estimated by an equilateral triangular prism with edges of length *l* :**

$$V_b = \tfrac{1}{2} w l^2 \sin(60^o)$$



- **Volume of regolith collected with each bucket pass is some fraction of V_b (multiply by bucket filling efficiency)**

REMOTE – Power modeling

- **Number of required charges during task completion calculated based on energy spent executing task, and battery energy storage**

- **10% of vehicle mass budget set aside for batteries**

- **Lithium Ion batteries with 150 W-hr/kg energy density**

- **2 hr charging time**
  - If the power available for recharge at the charging station is capped, larger vehicles will require more time than smaller ones to reach full charge, thus adversely affecting the computed advantage of a 300 kg machine

- **Hotel power of 80 W assumed for electronics and other systems, and added to driving and excavating power**

REMOTE – Power modeling

Power consumed while driving is estimated by:

$$P^{\text{driving}} = \mathrm{K}_{\mathrm{Pd}} * mg * v$$

Power consumed while excavating is estimated by:

$$P^{\text{excavating}} = \mathrm{K}_{\mathrm{Pex}} * H_F * v_{ex}$$

Operational duty cycle

- **Illumination efficiency of 70% is assumed for lunar pole**
- **Of the illuminated time, only a fraction is assumed to be spent operating (operational efficiency)**
  - An efficiency multiplier is applied to account for operation planning, reduced situational awareness, etc.

Legend – Variable Parameters Examined

Parameter	Symbol	Expected value	Reference
Lunar Environmental Parameters			
Lunar gravity	g	1.62 m/s^2	LSB
Minimum lunar regolith angle of internal friction	φ_{min}	35^o	Wilkinson07
Minimum lunar regolith cohesion	c_{min}	170 N/m^2	Wilkinson07
Maximum lunar regolith cohesion	c_{max}	1100 N/m^2	LSB, p. 510
Maximum lunar regolith bulk density	$\gamma_{b,max}$	1920 kg/m^3	LSB, p. 494
Bulk density of lunar regolith compacted to 75% relative density	ρ_{berm}	1765 kg/m^3	Calculated value, based on LSB
Minimum bulk density of excavated lunar regolith	ρ_{ex}	1450 kg/m^3	LSB, p. 484

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Legend – Variable Parameters Examined

Concept of Operations Parameters			
Berm diameter	D	50 m	Mueller08b
Plume ejecta angle	α	3°	Mueller08b, Lane08
Berm height	H	2.6 m	Calculated value
Berm top width	W_t	0.6 m	
Berm slope angle	θ	50°	
Berm arc angle at center	ψ	180°	Mueller08b
Total volume to excavate	V_{ex}	710 m³	Calculated value
Maximum required excavation depth	d_{ex}	36 cm	Calculated value
Average transport shuttle distance	x_t	25 m	Calculated value
Shuttle recharge distance	x_r	500 m	
Transport shuttle velocity	v_t	15 cm/s	
Recharge shuttle velocity	v_r	15 cm/s	

Legend – Variable Parameters Examined

System Parameters			
Number of robots	N	2	
Individual vehicle mass	m	150 kg	
Ground contact area	A_G	0.3 m^2	
Excavation depth	d	5 cm	
Excavation rake angle	β	20^o	
Bucket length	L	14 cm	Calculated value
Bucket width	w	88 cm	Calculated value
Bucket volume	V_b	0.0072 m^3	Calculated value
Trickle power	$P_{Trickle}$	0 W	
Hotel power	P_{Hotel}	80 W	
Fraction of mass budget for batteries	$m_{\%batt}$	10 %	
Battery energy density	SE	150 W·hr/kg	LSMPR
Battery charging time	t_{batt}	2 hr	

Legend – Variable Parameters Examined

Efficiency Parameters			
Fraction of traction available for excavation	K_{HFT}	60 %	
Bucket filling efficiency	η_V	50 %	
Driving power coefficient	K_{Pd}	2	
Excavation power coefficient	K_{Pex}	2	
Light availability percentage	η_{light}	70 %	
Operational efficiency	η_{Op}	60 %	

REMOTE uses the Viking excavation model

- **Viking is simple and conservative**
- **Viking model is more conservative than 2D Balovnev model**
- **The models could serve as upper and lower bounds for excavation force**
- **There are a number of excavation models, of which the Viking and Balovnev models are common for use in designing for planetary surfaces**

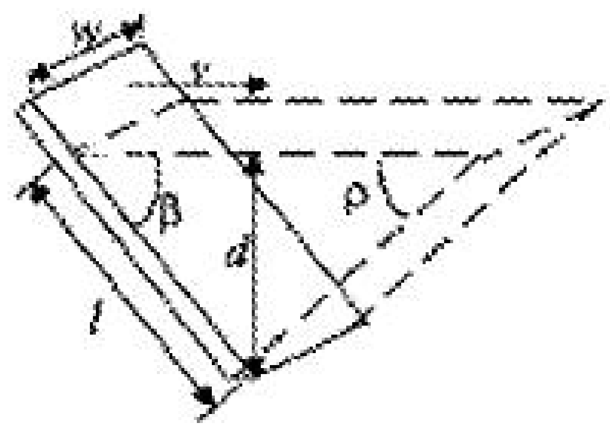
Comparison of excavation models

Model		Osman	Gill & Vanden	Swick & Perump-ral	McKyes	Vi[illegible]ng	Ba[illegible]vn -ev
Dimension		2	2	2	2	2	2 or 3
# of Parameters	Geo.	5	4	3	3	4 (3)	8
	Terrai n	4	5	7	7	2	5
	Grav.	1	1	1	1	1	1
	Speed	0	1	1	1	1	0
	Etc.	7	0	0	0	0	1
	Total	17	11	12	12	8 (7)	15
Problem		Need iteration	Math. singularity	-	Math. singularity	-	-
Digging depth for given force (~240N)		-	<0.05 (m)	0.15 (m)	0.15 (m)	0.062 (m)	0.14 (m)

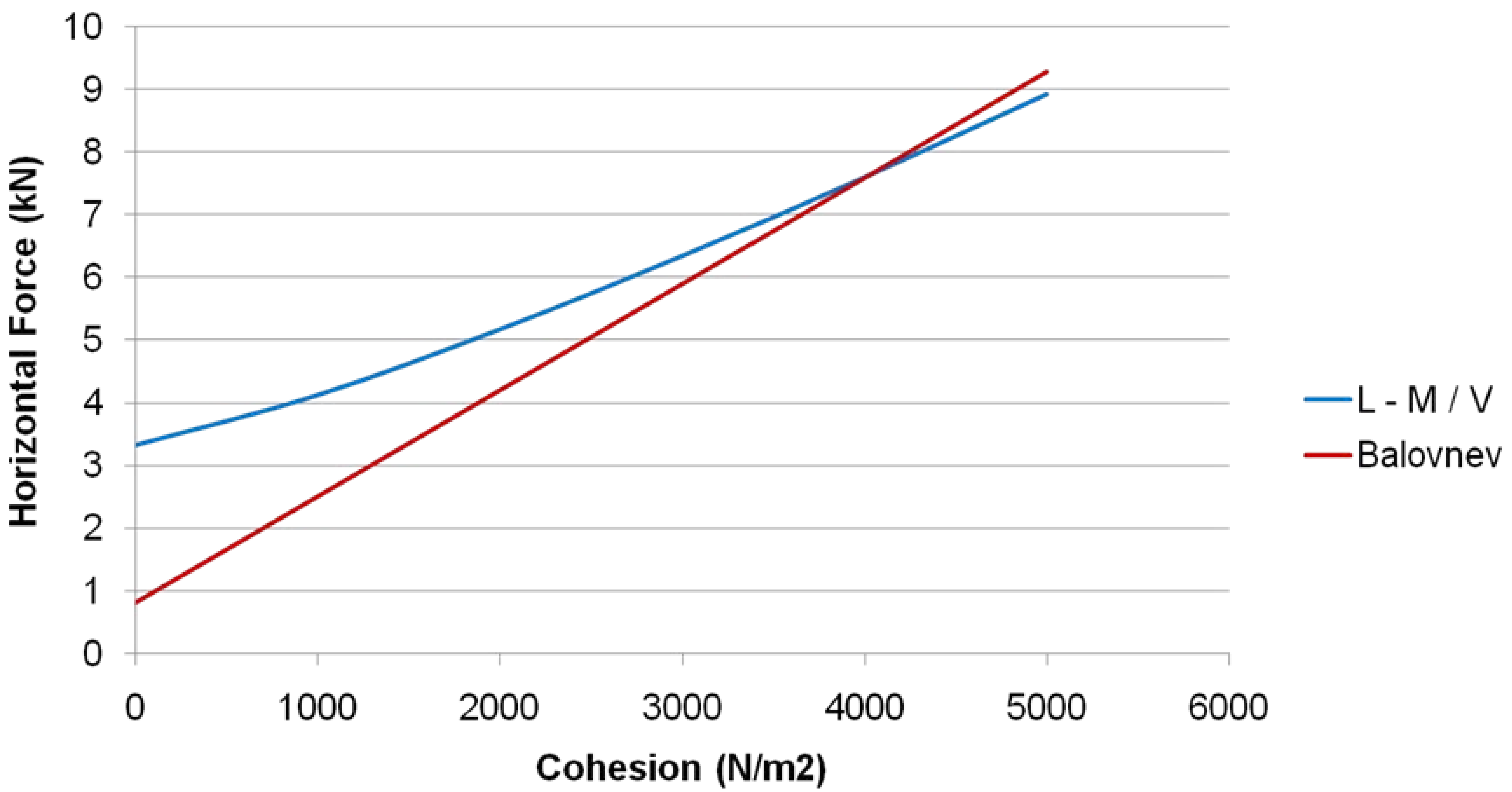
Baseline parameters for model comparisons

Parameters

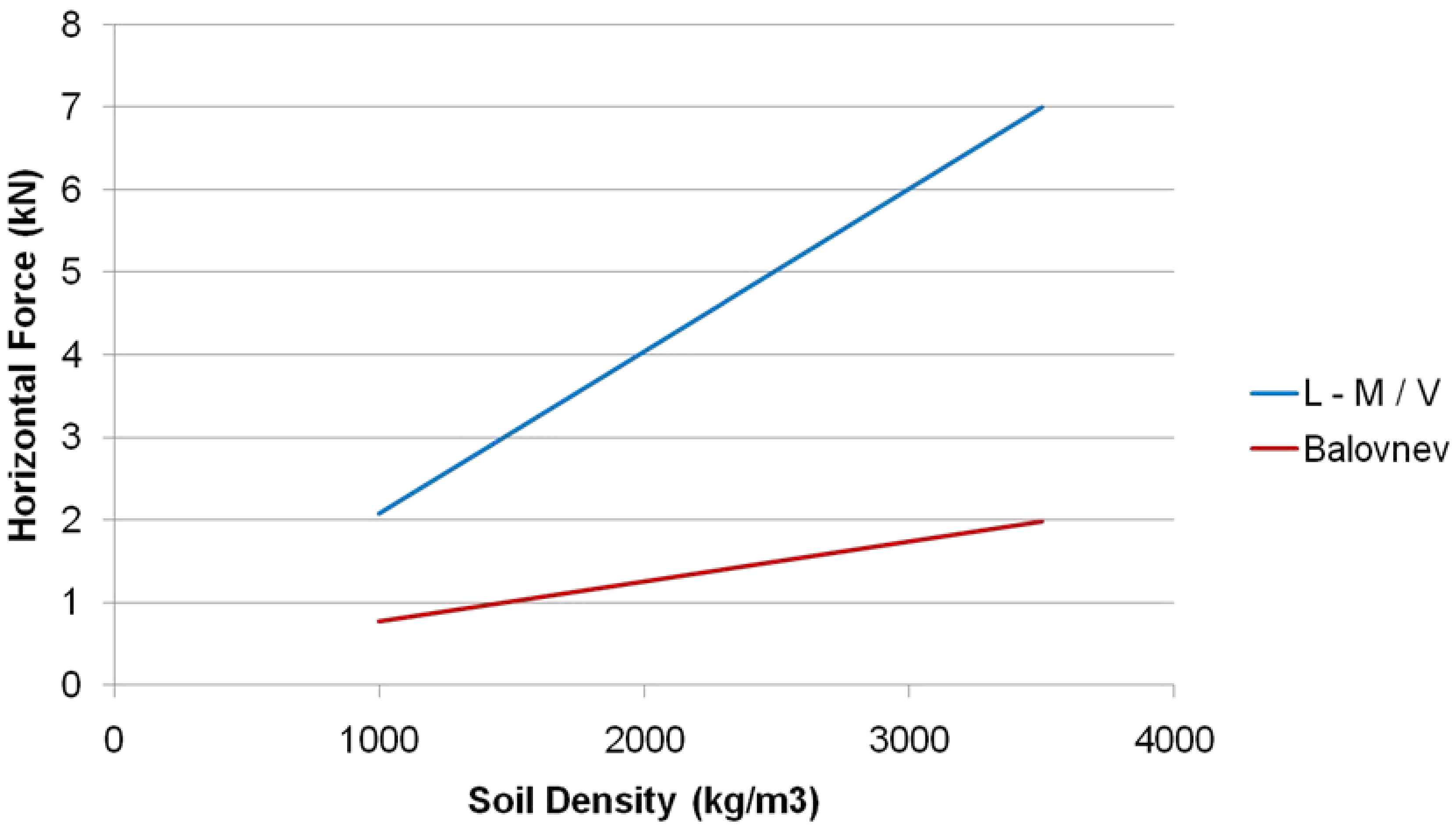
CONSTANTS			
Soil specific mass	gamma	1680 kg/m^3	
Moon gravity	g_M	1.63 m/s^2	
Cohesion	c	170 N/m^2	(Terrain dependent)
Total width	w	1 m	
VARIABLES			
Tool length	l	0.7 m	
Tool depth	d	0.5 m	
Rake angle	beta	45 deg	
		0.785 rad	
Tool speed	v	0.1 m/s	



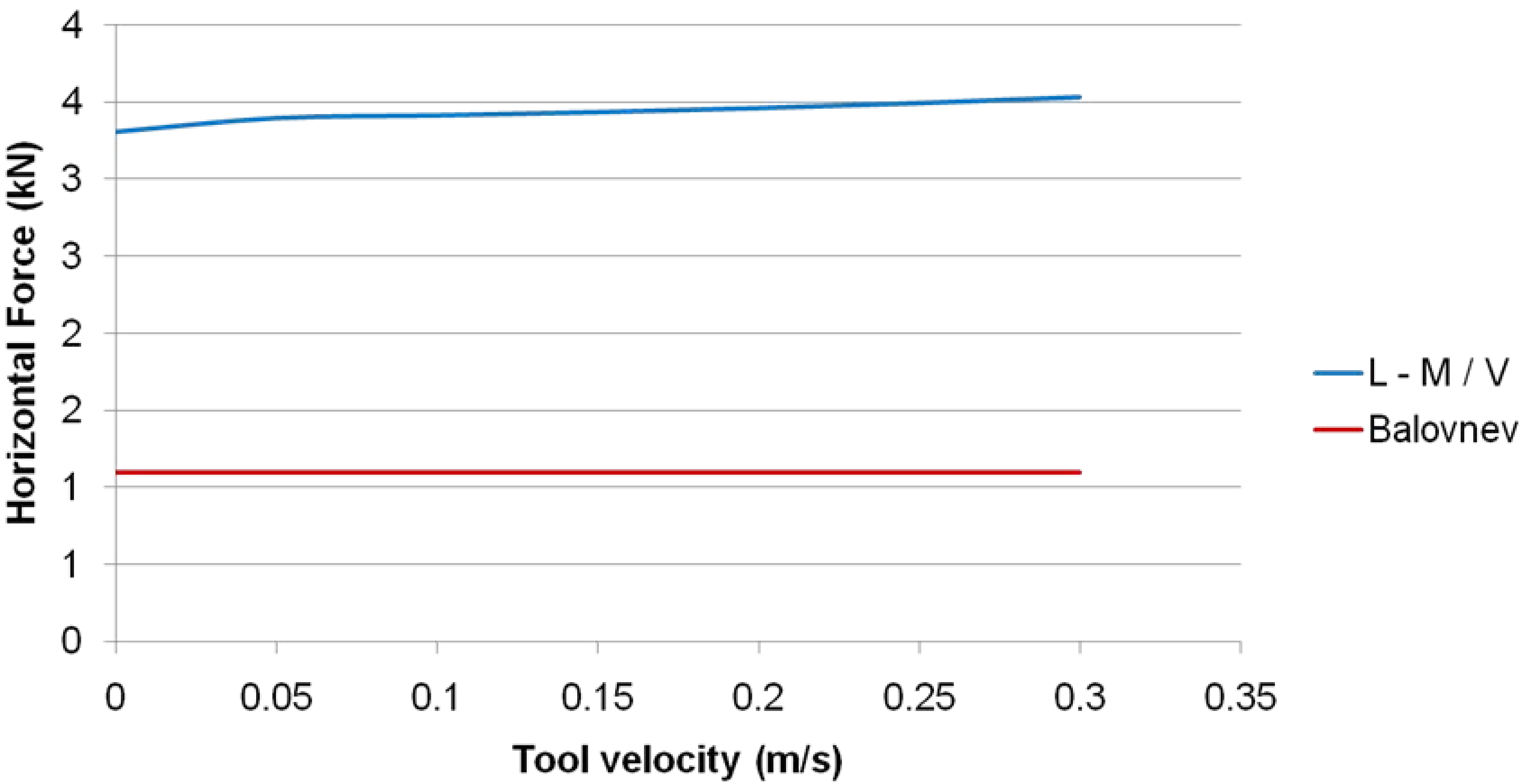
Excavation models



Excavation models

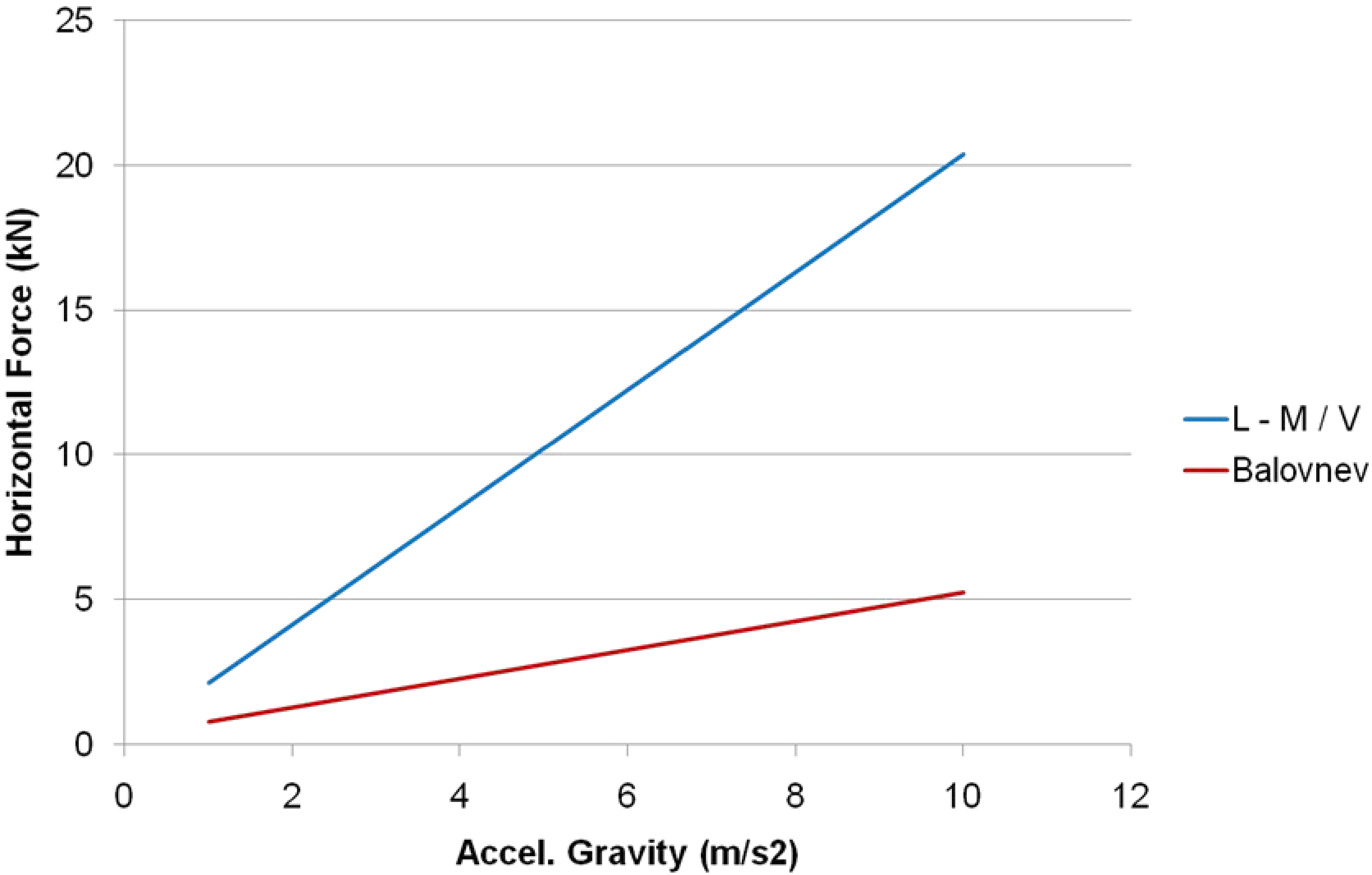


Excavation models

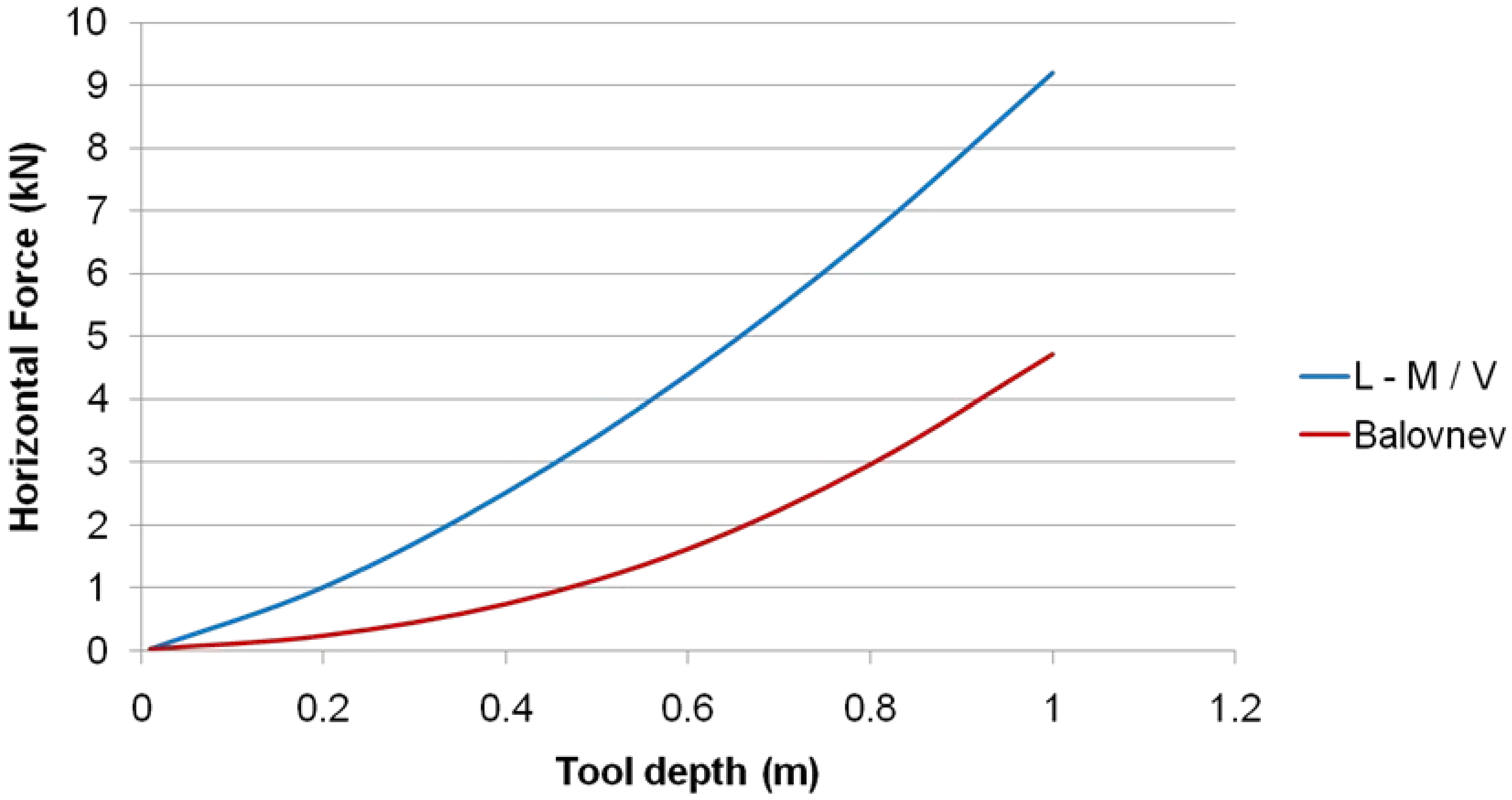


- **Excavation force is independent of tool velocity in the Balovnev model**

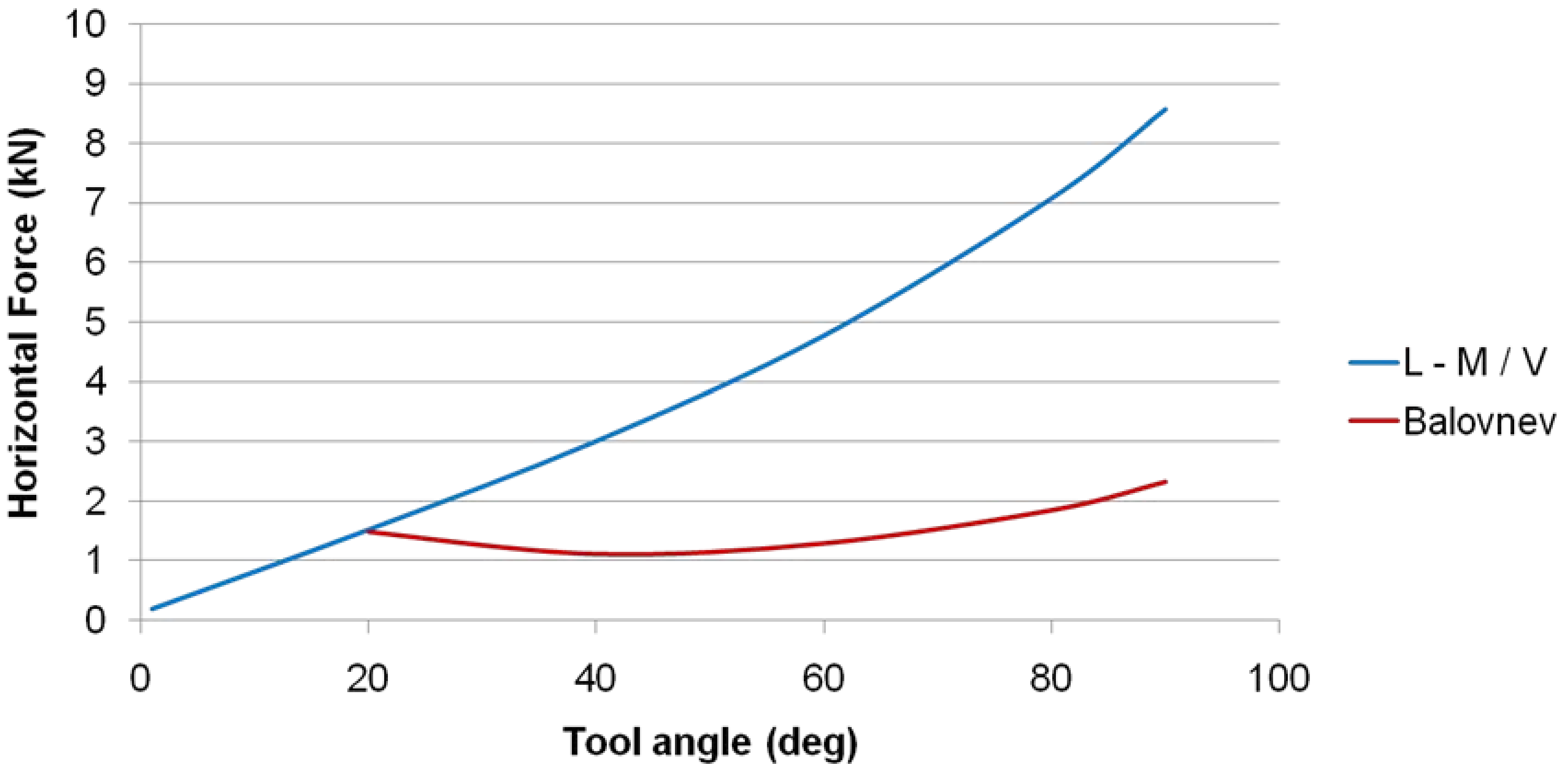
Excavation models



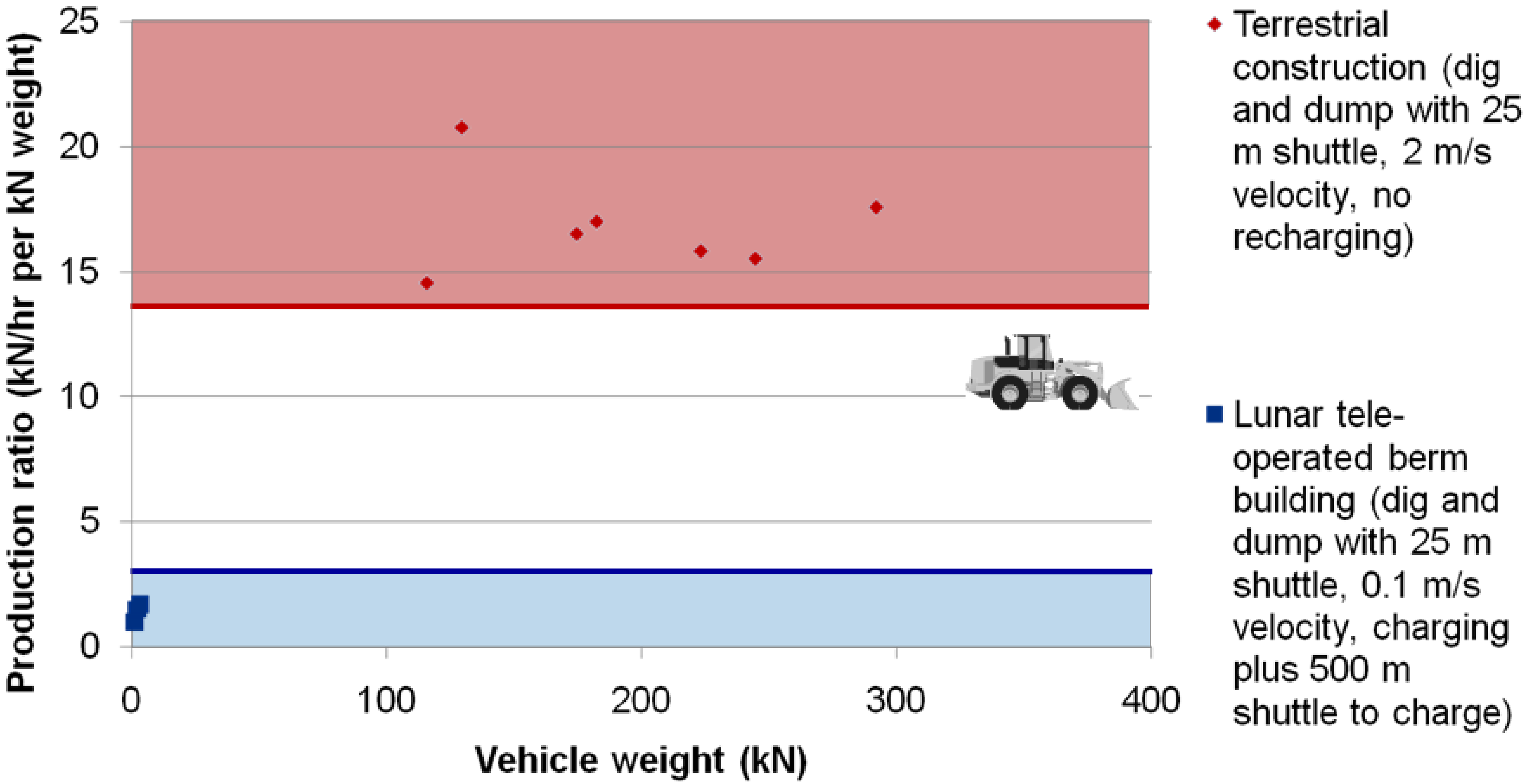
Excavation models



Excavation models



Wheel loader production ratios by weight and task



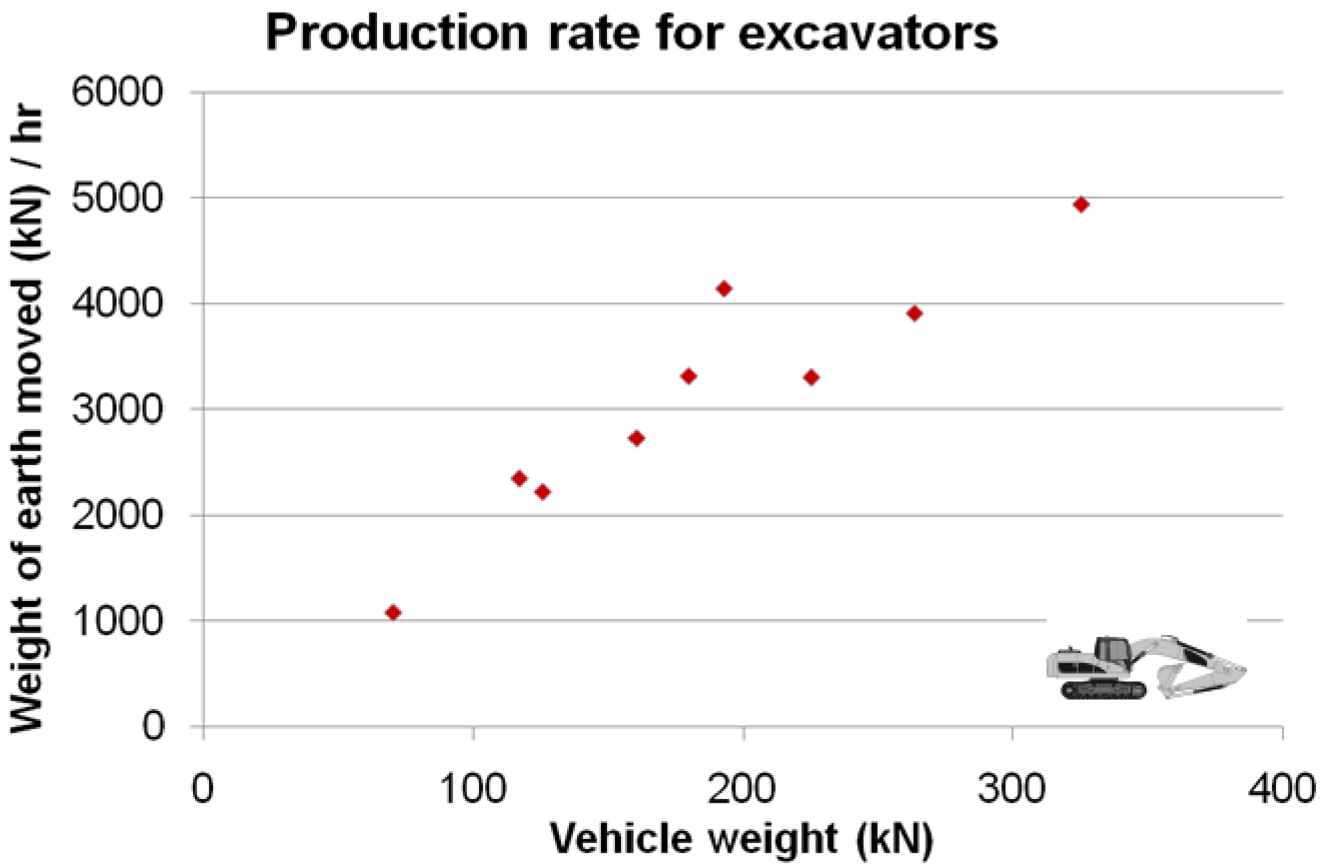
- **A machine's production ratio is the weight it can dig and dump in an hour relative to its own weight**

Berm building task incorporating different machines

- **300 kg machines converted a higher percentage of total task energy into berm-building work**
- **100 kg machines spent a larger proportion of their task-completion time charging batteries**
- **Some of the key assumptions that lead to these factors:**
  - The hotel power (baseline during idling) stays constant with changing mass (for the class of 100 kg to 300 kg machines), and is a large proportion of their total task power
  - The proportion of the mass budget allocated to batteries stays constant with changing mass
  - Significant time is required to charge batteries
  - Size does not significantly influence the operating velocity

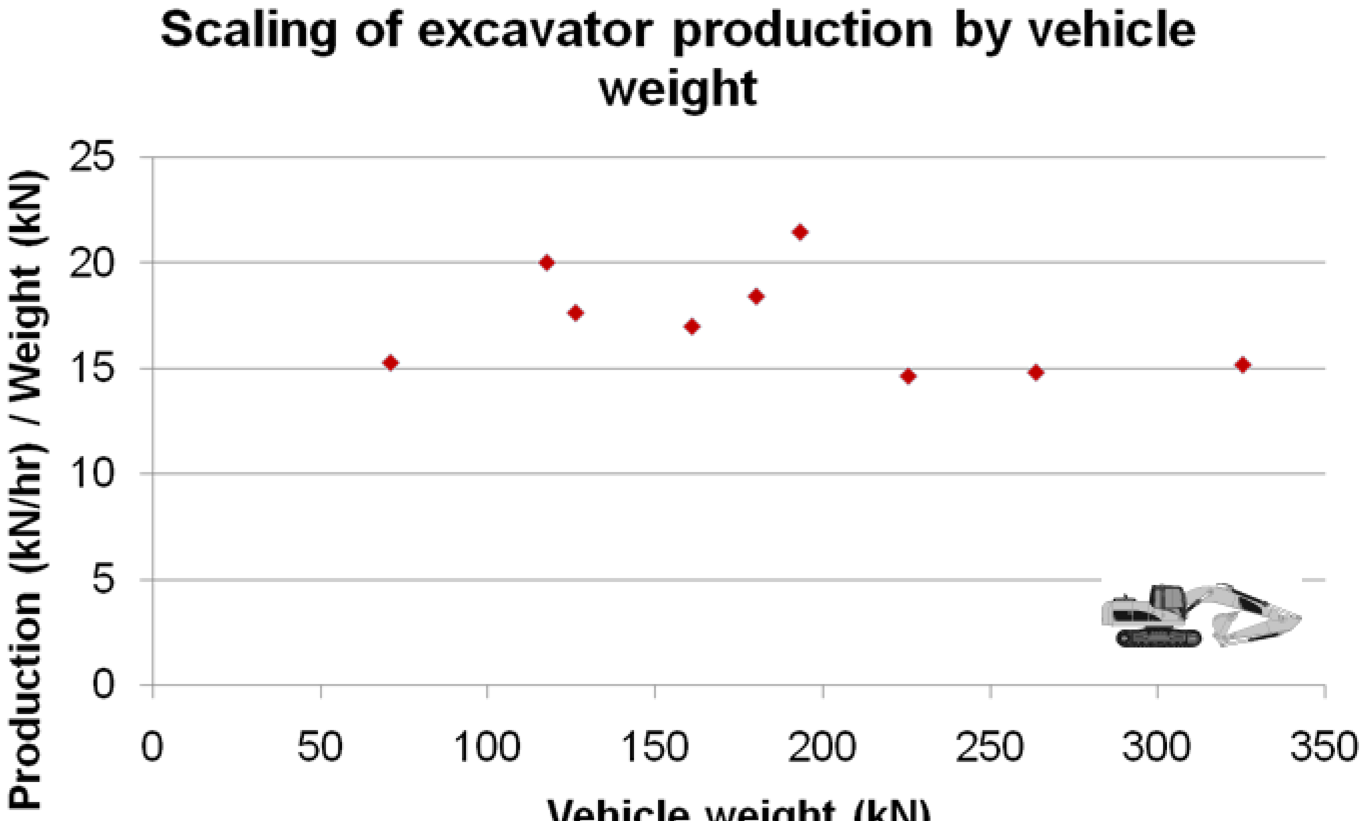
Terrestrial equipment

- **Production rates for terrestrial excavators increase with size of machine**



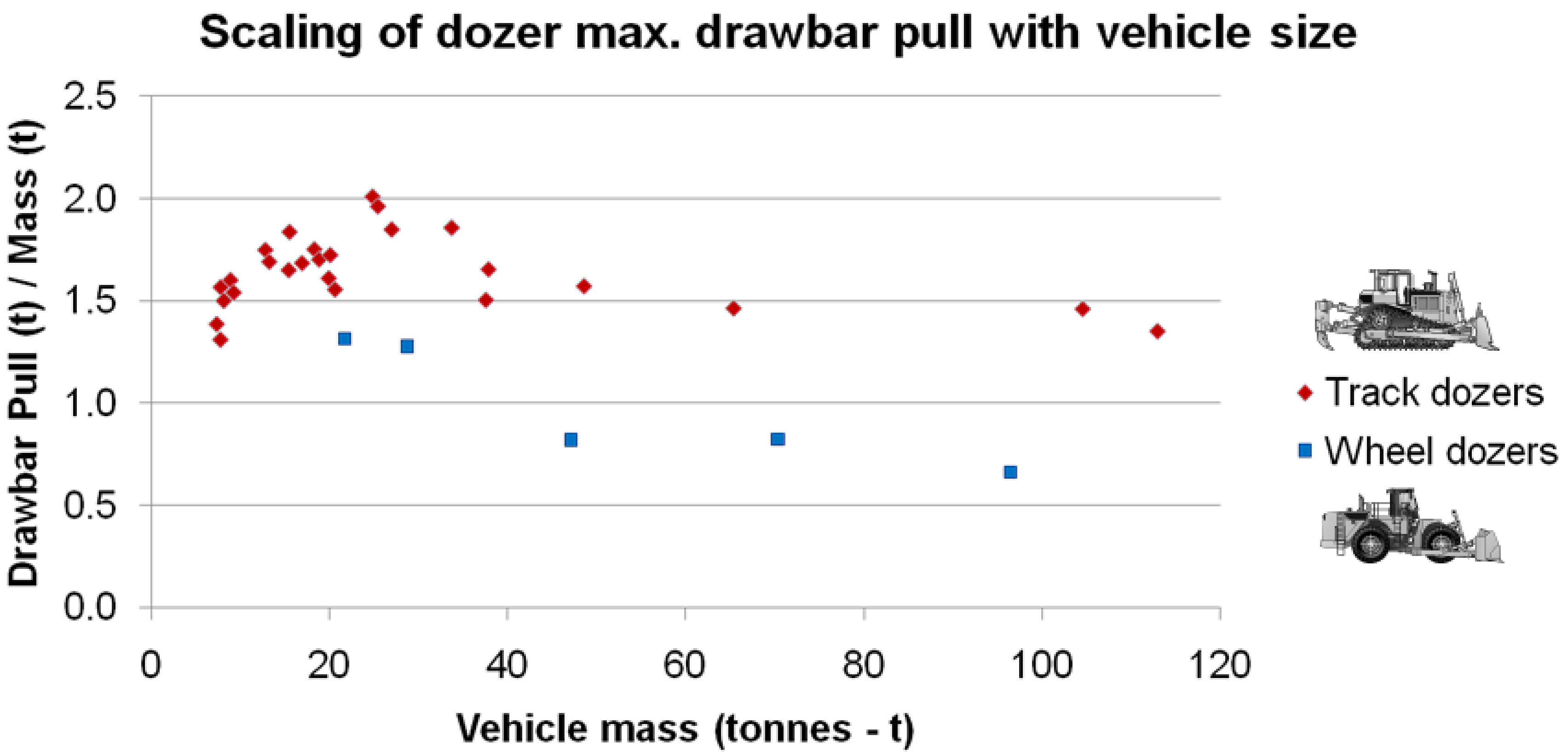
Terrestrial equipment

- **Scaling production by vehicle weight shows that advantages of larger vehicles may not carry over on a pound-for-pound basis**



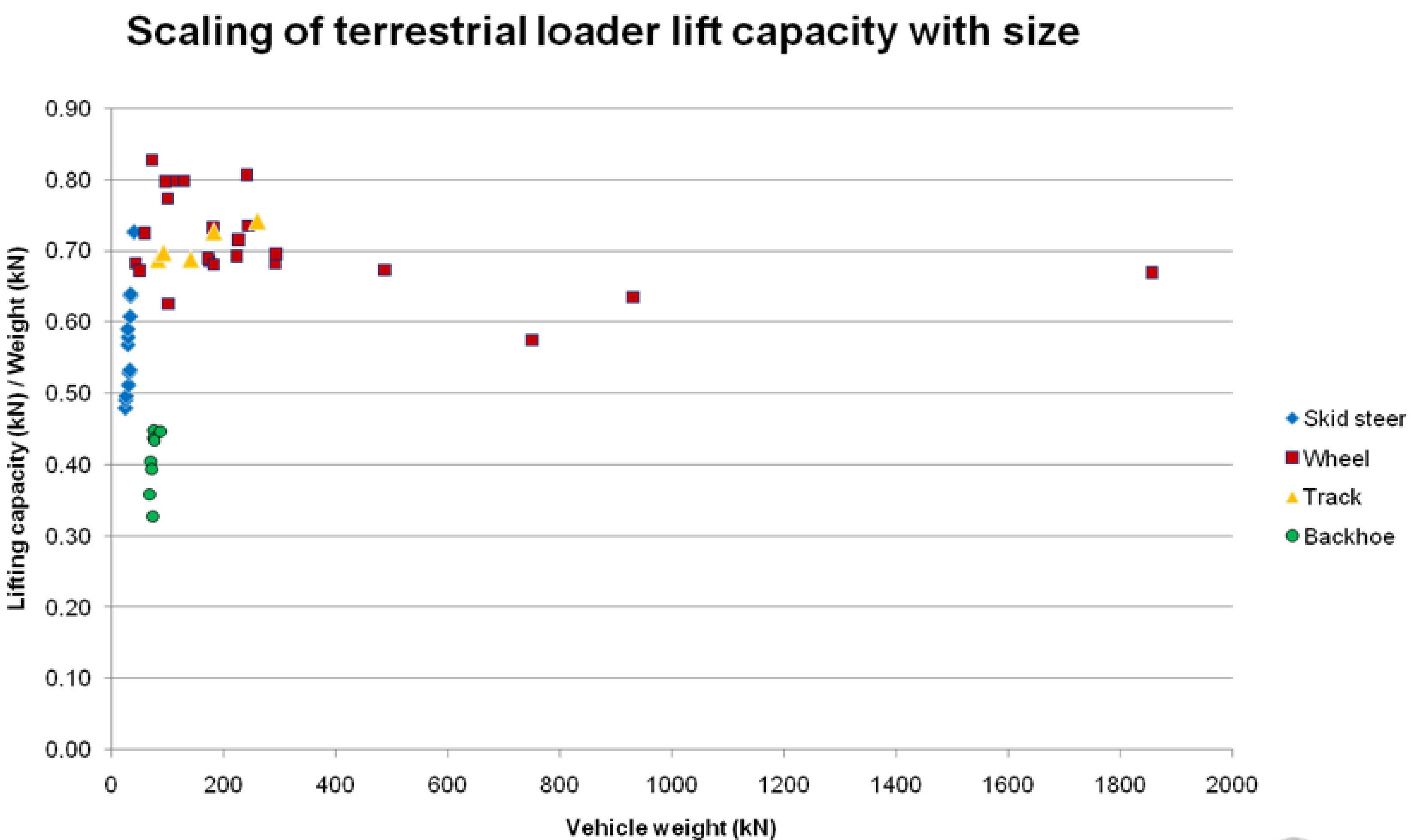
Terrestrial equipment

- **Scaling forces by vehicle mass shows that highest drawbar pull is in the low- to mid-mass range**



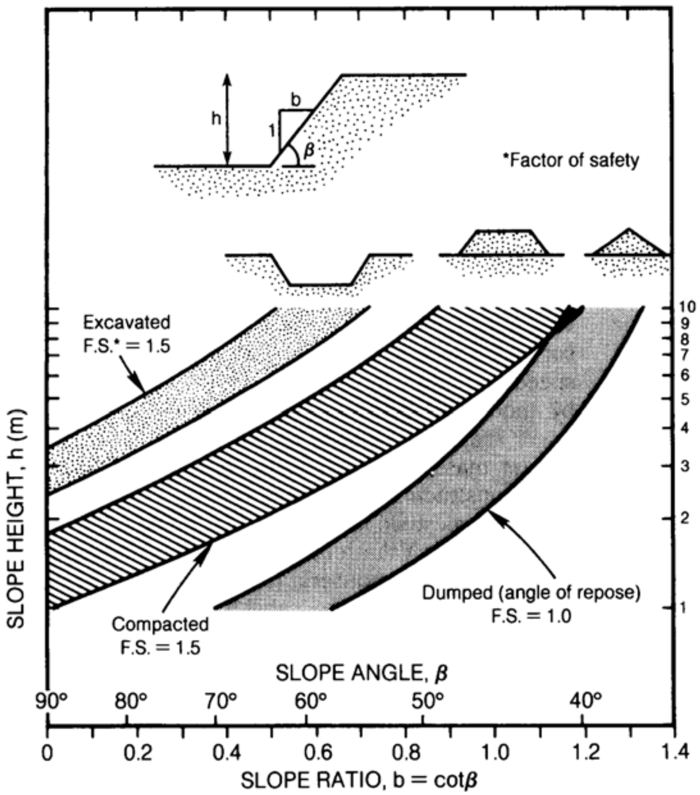
Terrestrial equipment

Payload ratios of terrestrial loaders



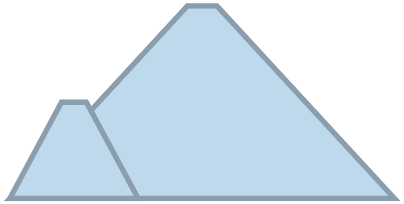
Regolith compaction

Compacted regolith can be piled in steeper berms:



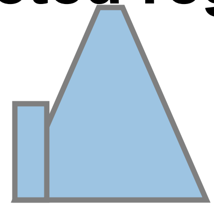
Regolith compaction

Uncompacted regolith (1380 kg/m^3):



- 1.5 m high berm will pile at 59^o, requires 2,490 kg/m
- 3 m high berm will pile at 46^o, requires 13,240 kg/m

Compacted regolith (1650 kg/m^3):



- 1.5 m high berm will pile at 90^o, requires 740 kg/m
- 3 m high berm will pile at 65^o, requires 8,410 kg/m

Such results may merit investigating means of compaction:

- Vibratory compactors, rollers, block compactors (sandcastle buckets)